A SIMULATION STUDY OF THE LM-2500 GAS TURBINE ENGINE INVENTORY SYSTEM

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THESIS

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ABSTRACT

LM-2500 gas turbine engine rotable pool requirements were studied using computer simulation. System operating characteristics were observed with various scenarios and management philosophies. Several purchase plans were formulated and tested once system trends were established. From this information, cost-effectiveness relationships were derived.

Best estimates of system variables indicated that cost-effectiveness was optimized for a rework capacity of seven to eight engines and the purchase of fourteen to sixteen engines early in system life as rotable pool spares.

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I. INTRODUCTION

The U.S. Navy has awarded a contract to Litton Industries Inc. to build thirty gas turbine powered destroyers. These ships, known as the Spruance or DD 963 class, are unique in many respects. They will be built by a single contractor in a new shipyard designed to employ the most advanced construction technology and mass-production techniques. Weapons systems will be off-the-shelf items but ample space, weight, and electrical power margins have been designed into the ships for future weapons systems modifications.

One of the unique features of the DD 963 class ships is their main engines. These engines are General Electric LM-2500 gas turbines, a marine version of the engine which powers the Lockheed C5A transport aircraft. The ships have been designed so that an engine can be removed and a new one installed in less than twenty four hours. Except for a crane, special equipment is not required by the ships crew to effect an engine change. This allows the engines to be designed for virtually no shipboard maintainence; consequently, a substantial saving in manpower is realized. Another result of this quick-change capability is that shipyard periods are independent of engine life and can therefore be scheduled at greater intervals.

Utilization of a quick-change capability requires the maintainence of a rotable pool from which replacements for high-time and failed engines can be drawn. This study, requested by the DD 963 project manager, addresses the problem

of determining the pool size required to support a growing fleet of turbine powered destroyers.

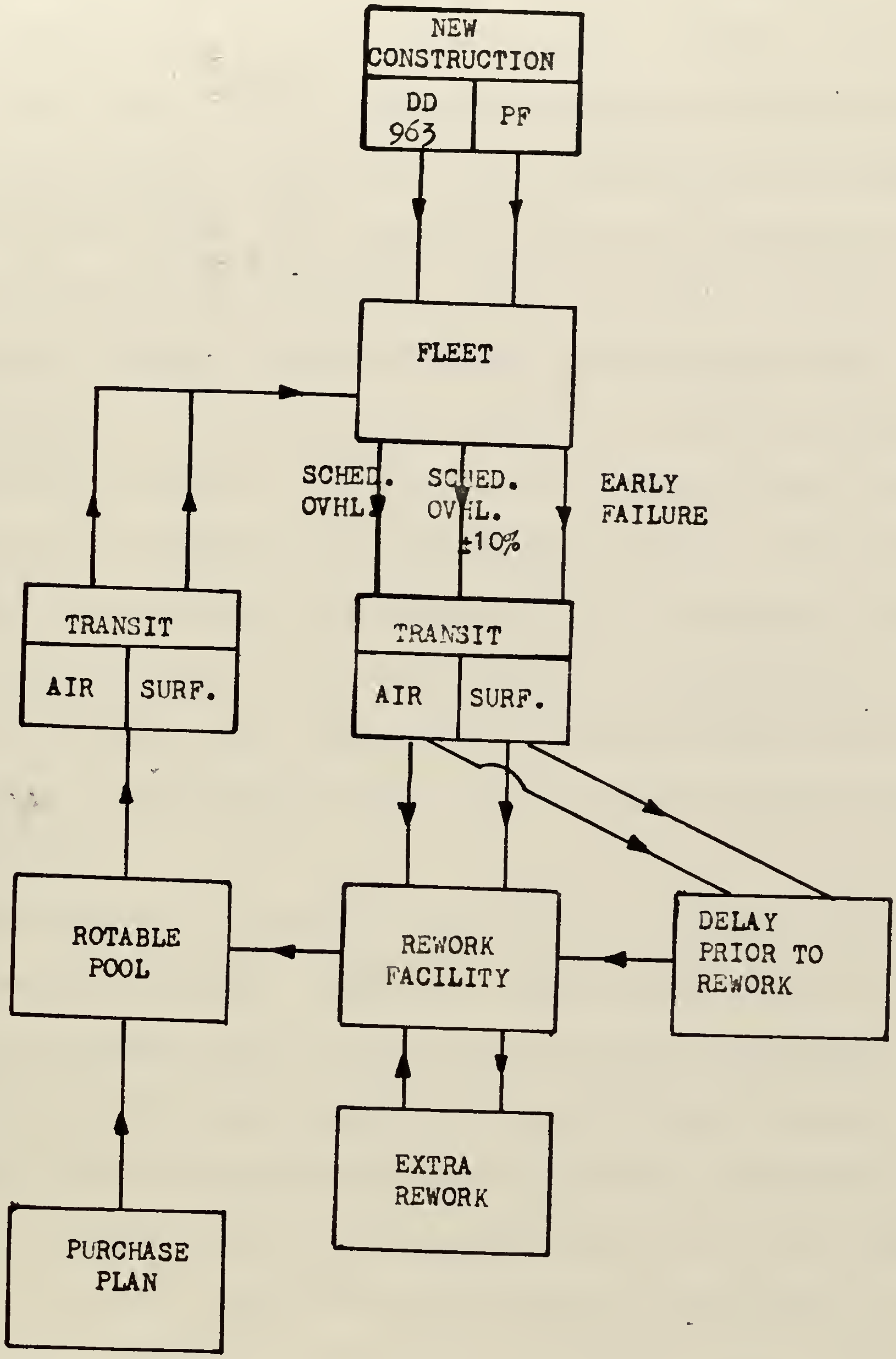
II. NATURE OF THE PROBLEM

A. GENERAL

DD 963 class ships will require a rotable pool of spare engines as part of the maintenance plan. Whenever an engine installed in an operating ship fails or accumulates a specified number of operating hours it will be removed from the ship and sent to a rework facility to be overhauled. The removed engine will be replaced by a new or previously overhauled engine from a pool of ready for issue engines. After the engine is overhauled it is stored in a ready for issue condition until it is required to replace another engine in the fleet.

The objective of this study is to determine the number of engines, in addition to those installed in the ships, required to maintain various levels of engine availability. A secondary objective was to study the effect of the PF program on pool size. The PF program, as proposed, includes construction of 50 escort ships beginning in 1978, each of which would have two LM-2500 engines, significantly increasing engine population.

Figure 1 shows the flow of engines during the life cycle of the DD 963 and PF class ships. This is the system which was simulated to meet the objective of the study. It is basically a closed loop system with two external inputs. The construction schedules for DD 963 and PF class ships introduce engines into the system, thus starting it operation. The purchase plans provide spare engines at various



ENGINE FLOW PATHS

FIGURE 1

points in time to keep the system operating smoothly. Within the closed loop portion of the system, engines leave the fleet when they fail, at scheduled overhaul, or at variable scheduled overhaul depending on the operating philosophy in effect at the time. The engines are then transported to the rework facility for overhaul. When the engines arrive at the rework facility they are either inducted into the facility for overhaul or they wait for induction if the facility is operating at capacity. They are then inducted when the facility can accommodate the additional engines. After the overhaul is completed, the engines go to a storage location (the rotable pool) until a requirement is generated by the fleet. At that time, the engine is transported to the ship requiring a replacement engine, thus completing the closed loop system.

This system is similiar to a single echelon, repairable item inventory system. However, this system differs from the normal inventory models in that both supply and demand are stochastic with supply dependent upon previous demand. In standard inventory models, the objective is to develop optimal decision rules to determine "when" and "how many" items to procure during the operation of the system. Due to the long budgeting and procurement lead times, the objective of this study is to develop information from which the decisions of "when" and "how many" can be made prior to the start of the system operation vice decision rules for use during system operation.

B. ASSUMPTIONS

Several simplifying assumptions were made in order to reduce the system to its essential elements. It was felt that the assumptions made would not appreciably affect the accuracy of the model.

The first assumption made was that all engines in the fleet would accumulate operating hours independently. It was felt that the largest part of any dependence which existed in the system would be among engines on individual ships. This dependence would possibly be different for the various ships depending on their Commanding Officers' engine operating policies. Computer programming problems as well as a lack of knowledge about the nature of these relationships made their inclusion infeasible. This assumption should not significantly affect the results of the simulation since sets of four engines are relatively small components of a 120 engine population.

Another assumption made was that reworked engines are as good as new. This implies that all engines entering the fleet will be fully reworked and considered zero-time engines. This eliminates the possibility of some engines being selectively repaired and returned to the fleet with a shorter time to overhaul.

It was assumed that ships will always have engines if available. This assumption eliminates the possibility of a ship's engines being removed at the start of a yard period, being reworked, then returned to the same ship. If

an engine must be replaced, one is sent from the pool immediately; if an engine is not available, the fleet is considered to be short one engine until one becomes available.

The entire engine assembly was considered as a single entity by assuming that the gas generator and power turbine had the same overhaul schedule. It was also assumed that when an engine fails, both major components must be removed and completely overhauled.

Random engine failures were assumed to be distributed uniformly on the time interval from installation to scheduled overhaul. This increasing failure rate distribution was considered to be more convenient than a truncated exponential distribution. The exponential distribution was used only to convert failure frequencies in the Maintenance Engineering Analysis (MEA) to an estimate of the probability of an engine failing prior to its scheduled overhaul.

Transportation time was assumed to include engine removal and replacement time. For scheduled engine changes, it was further assumed that engines would be shipped from the pool to arrive in time for the change. Transportation time includes time for old engine removal and shipment time to the rework facility then to the pool. For random failures, the replacement engine was delayed enroute to the ship for a time equal to transportation time.

It was assumed that input rates were deterministic. The function which loads ships into the GPSS program was derived from planned ship launch dates, but can be changed easily.

The overhaul times used are estimates by officals at Kelly Air Force Base of the time it would take to overhaul the LM-2500 engine. Air Force estimates were based on actual rework of a version of this engine, thus their estimates were considered reliable. It was assumed that these estimates would reflect all factors affecting the rework time such as parts shortages, labor problems and accidents, etc. It was further assumed that there would be only one facility since it is not likely that the Navy will have enough LM-2500 engines in the foreseeable future to justify more than one.

III. THE MODEL

A. REASONS FOR SIMULATION

Preliminary analysis of the DD 963 inventory problem disclosed that system complexities rendered analytical modeling infeasible. In view of this fact, a computer simulation was determined to be the most promising form of analysis. Additionally, simulation offers the advantages that as data becomes available, the model can be updated to reflect "real world" changes. Computer simulation further offers the analyst the ability to vary key parameters across their ranges of uncertainty, deriving in the process, worst, expected, and best case estimates.

B. MODEL DESIGN

A combination GPSS and FORTRAN model was developed, and designed so that changes in system configuration could easily be incorporated. Data gathered from the GPSS model is fed onto a magnetic disk where it is stored until used by the FORTRAN program. The advantage of this linkage is that it frees the analyst from the intermediate step of assembling the data to input the FORTRAN section. An accompanying disadvantage is that this disk linkup must be altered slightly to conform to the features of the computer system being used. Depending upon model configuration, approximately one minute of computer time is needed to simulate five years of system life.

[illegible]

C. GENERAL DESCRIPTION

The simulation was constructed in modular form to permit the maximum amount of flexibility in modeling various states of the system as well as in changing the output statistics desired. There are two main and seven secondary sections in the program. They are listed below and described in the following sections.

1. GPSS Section

a. The base case consists of the basic simulation with the DD 963 input.

b. The base case with the PF load allows the addition of PF engines to the base case.

c. Management options allow the extention of TBO by some specified amount contigent upon rework facility load.

d. Purchase plan option allows the testing of various purchase strategies to determine cost and expected outages.

e. The split rotable pool option allows the testing of the effect of using two rotable pools.

f. The statistics section accumulates the data that is desired from the GPSS program.

2. FORTRAN Section

a. SUBROUTINE READ reads the data from the disk to input the FORTRAN program.

b. SUBROUTINE CLIM reads data provided by READ and computes confidence limits on number of engines required.

c. SUBROUTINE COST calculates twenty year life cycle costs of the rotable pool.

D. OPTIONS OF THE MODEL

1. Option 1

The primary model (option 1) consists of those components which are necessary to mimic the DD 963 program. Engines are delivered (zero-timed) into the fleet with the launching of each ship. The engines then accumulate time as a function of their operating schedule which is a "Model Variable" (MV). Engines may fail early with some probability (MV), or they continue in service until they accrue TBO, at which time they are replaced. Engines replaced for either reason are shipped to a single rework facility incurring some transportation delay (MV) enroute. Upon arrival, they wait for an opening; if the rework facility is operating at less than capacity (MV) they are inducted immediately. Rework capacity is defined to be the number of engines which can be in rework simultaneously. Once in rework, the engines are overhauled, their rework time being a function of how many LM-2500 engines the facility has overhauled. Upon completion of overhaul, engines are then shipped to the rotable pool with some transit time (MV). Once in the rotable pool, engines wait until they are demanded by the fleet. It should be noted here that a large number of engines are preloaded into the pool. In this way demand is always satisfied and engine requirements may be measured as the number of engines actually removed from the pool.

Engines which are replacements for those engines which have failed unexpectedly travel from the rotable pool

to the fleet with some delay (MV). The reworked engines then commence the same cycle.

2. Option 1 With Patrol Frigate Program

Option 2 consists of the PF LOAD superimposed on option 1. At some time after the launching of the DD 963 the patrol frigates engines arrive in the fleet at the rate of two per month (MV) until the fiftieth PF launches. Any number of PF's may be simulated, as well as any schedule.

3. Management Options

Option 3 differs slightly from Option 1, in that the times at which engines may be replaced can now be controlled, except for those engines which fail prematurely. Engines which do not fail prematurely may be removed early or late by some percentage (MV) of replacement time. Engines are extended in-service contingent upon rework facility load. If the load is less than some number of engines (MV) undergoing rework, then the engine is inducted. If facility load is greater than that deemed appropriate for early induction, the engine continues in service until either the facility load drops, or the engine reaches TBO plus some percent of TBO, i.e. TBO+10%. At this time, the engine is inducted regardless of facility load. In this option, there is also the capability of considering deployed engines. Some percent (MV) of those engines not failing randomly are considered to be on deployment. A deployed engine is extended the full time allowed (MV) to permit completion of deployment without changeout.

4. Purchase Plan Options

This option allows the testing of various buying strategies in order to observe cost versus expected outage results. The simulation flow is as described for option 1, however, the rotable pool is now loaded according to some purchase plan, and it is possible for the pool to become empty. The number of engines bought each year must be specified for this input. The simulation proceeds as before, with the addition of a section to gather statistics on engine-weeks lost as a result of the particular purchase plan being tested.

5. Split Rotable Pool Option

This option is basically that of option 1 with the following proviso. There can be multiple pools, and they may be drawn upon only by those engines in the fleet they serve. In the two pool case - two fleets, operating independently, are each served by their own pool, but use the same rework facility. Additionally engines may not be shipped between pools. The model was not extended past two rotable pools.

E. MODEL OPERATION

The GPSS model is used to predict the 20 year life history of the engine inventory system. Statistics are gathered every 8 weeks (MV) on the number of engines in the pipeline. By taking repeated observations at a particular "time slice", the model obtains a distribution of the number of engines needed as a function of time and the

model parameters being used. The mean and standard deviation for all "time-slice" distributions are printed and the resulting confidence intervals displayed graphically by the computer. The result is the expected "history" of that particular model which can then be compared with other model versions to establish trends in model behavior.

A listing of the model parameters along with their descriptions may be found in Appendix E.

The model structure of GPSS normally accumulates statistics on key aspects of the system. These have been suppressed as extraneous to the problem at hand. Such statistics may be easily gathered to answer other "system" questions. Example of possible model-extension statistics are:

1. Average pipeline time (system).
2. Rework facility usage data.
3. Total transportation time.

Each distribution is based upon ten observations. Despite the loss of statistical accuracy, ten was determined to be the maximum feasible number of observations to make. System trends can clearly be distinguished at this level, and the accuracy that could be provided by increasing the number of runs does not warrant the required computer time.

F. LEVEL OF DETAIL

The model is not intended to reflect every detail of the "real world" system. Thus, for example, no attempt was made to maintain engine identity with its parent ship or shaft.

This would be a significant logic problem and the model would become at least one order of magnitude more detailed -- if the attempt were made to account for the statistical dependence that will probably exist in the real world. As a result, the assumption is made that the engine replacements are independent. It is felt that the current model can provide an adequate basis for analysis of major system trends. More succintly:

> "It is essential, therefore, to extract from the real system those factors and relations which have a significant effect upon the performance measure being examined and to disregard all unimportant details; keeping in mind, however, that what is deemed unimportant in one study may have vast implications in another" [Ref. 1].

IV. PRESENTATION AND ANALYSIS OF DATA

A. SELECTION OF THE BASE CASE

Due to the large number of variables in the problem, it was impossible to examine them in every possible state of nature. As a result, it was necessary to select an expected case and observe the effects of key system variables upon this "base case".

The system variables which follow are listed along with their sources and are individually the "most likely value" that the variable of interest will assume.

1. Fleet Operating Profile

The current operating profile of about 1650 eng. hrs/yr is assumed most likely. This information is derived from Fleet Fuel and Steaming reports [Ref. 4] covering the years 1965 to 1970.

2. Time Between Overhauls (TBO)

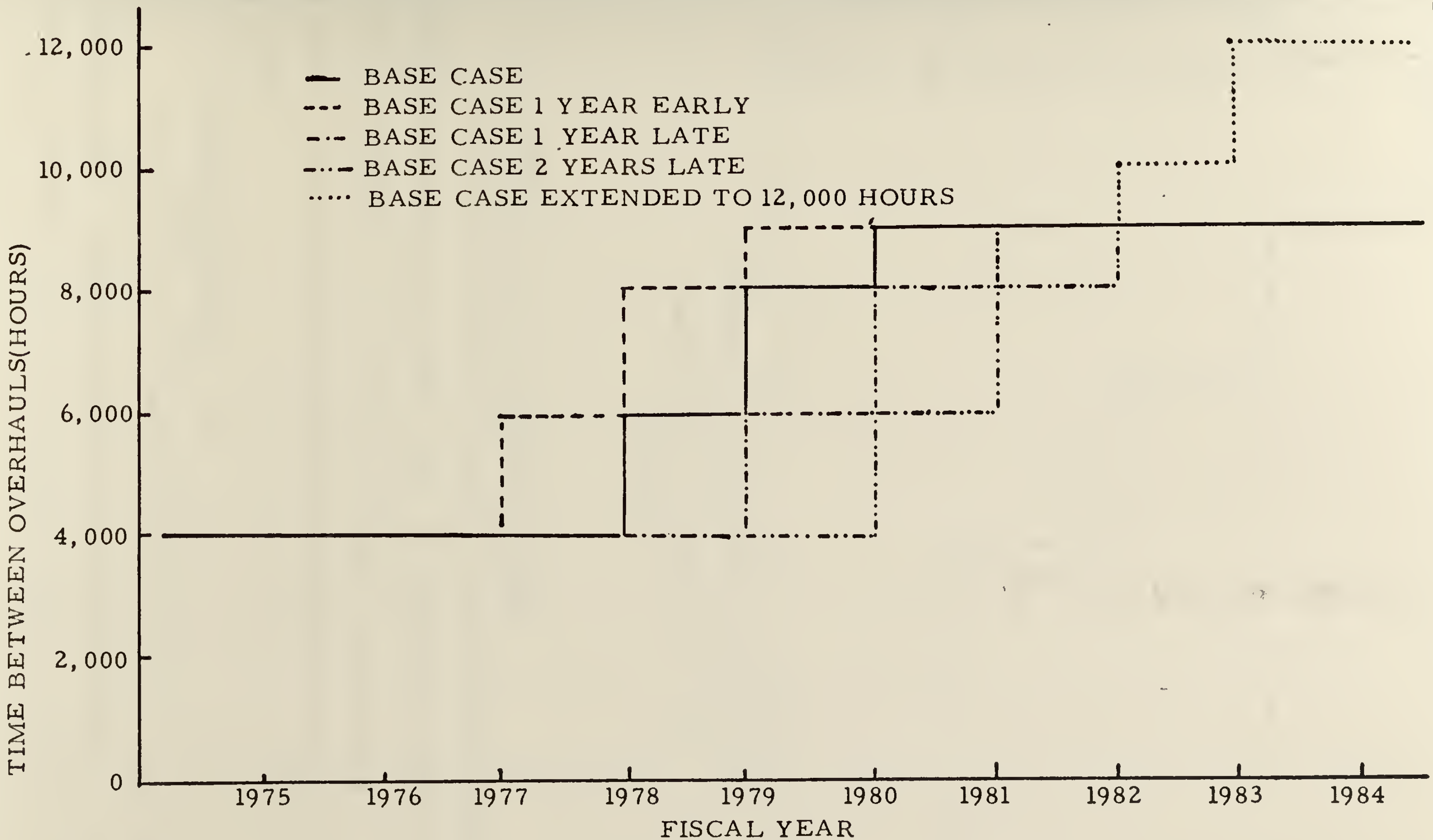
TBO is assumed to grow as specified in Figure 2. This estimate is furnished by PMS-389.

3. Rework Time

Overhaul time of the engines is expected to follow the learning curve in Figure 3. This estimate is furnished by officals at Kelly A.F.B.

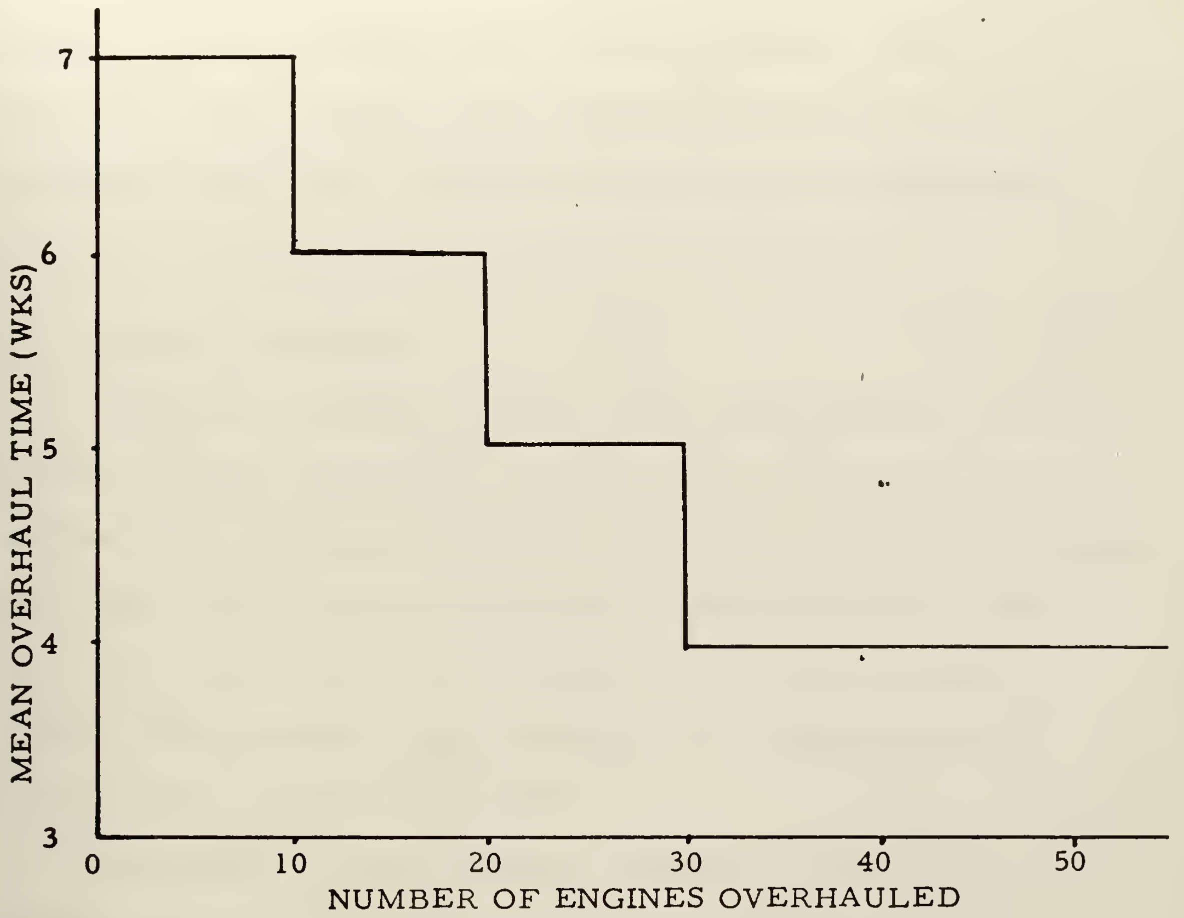
4. System Transit Time

It was assumed that these engines would be individually-managed high priority items. A mean system transit time of three weeks was assumed.



TBO GROWTH

FIGURE 2



ENGINE MEAN OVERHAUL TIME
FIGURE 3

5. Probability of a Random Failure

This percentage was derived from Litton's Maintenance Engineering Analysis (MEA) [Ref. 3] assuming a TBO of 6000 hours. A figure of 13.5% was obtained (Appendix C). Thus 13.5% of the operating engines are expected to fail prior to TBO.

6. Rework Capacity

Rework capacity was selected as four, i.e. four engines may be undergoing overhaul simultaneously. This is roughly the mean number of engines requiring rework in one

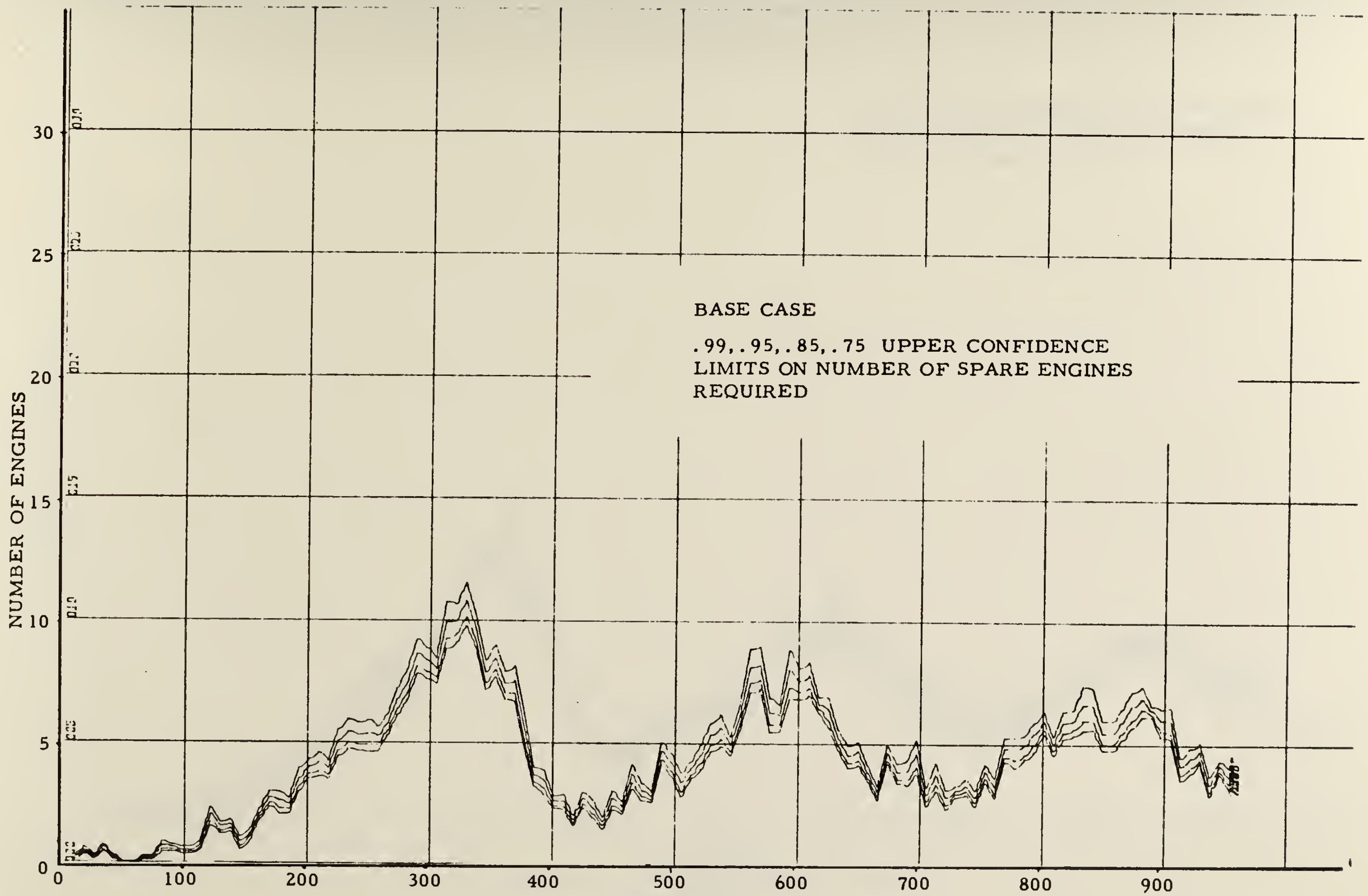
month without the load from the PF program. Four is not the most likely number for rework capacity, but rather the smallest value that can meet the base load requirements. In this respect, the base case is pessimistic.

B. NATURE OF RESULTS

Figure 4 is a plot of base case spare engine requirements at upper confidence limits of 99%, 95%, 85% and 75% as drawn by a computer operated plotter. All other figures show only 99% confidence levels. All confidence levels are calculated using the results of ten observations of system requirements and assuming that observations are distributed normally (Appendix D).

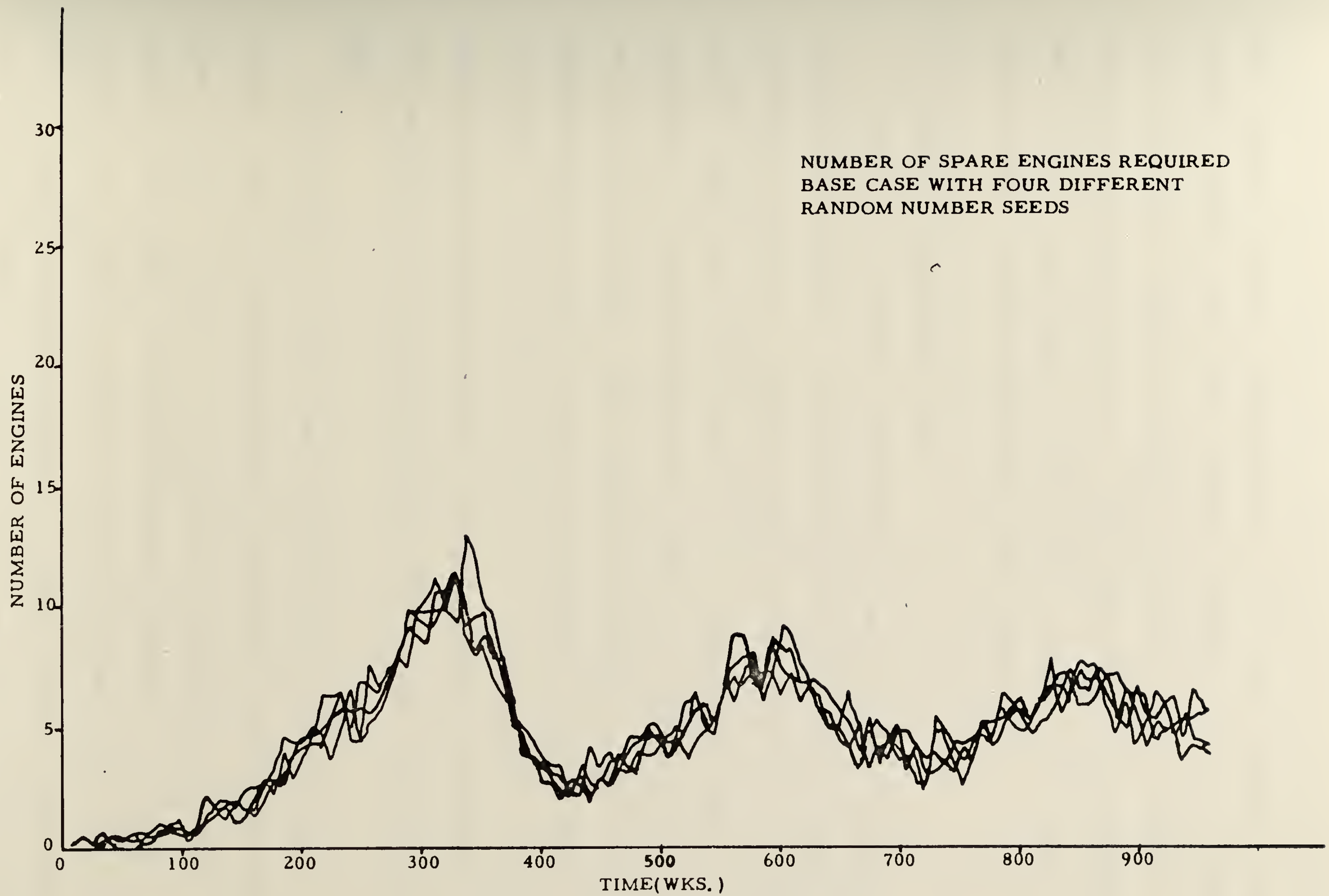
The number of spare engines required throughout the twenty year system life appears to be cyclic in nature with requirements, in most cases, rising to a global maximum near the three hundredth week of system life (fiscal year 1981). After the global maximum, requirements rise and fall in a cyclic manner. The magnitude and time of the various extreme points depend on the values of the input variables.

Figure 5 shows the base case (99% confidence limit) requirements from four series of runs of the simulation, each ten-run series made with a different random number seed. The coincident nature of the four plots indicates that the choice of random number seed will not significantly affect the results of the simulation.



BASE CASE RESULTS

FIGURE 4



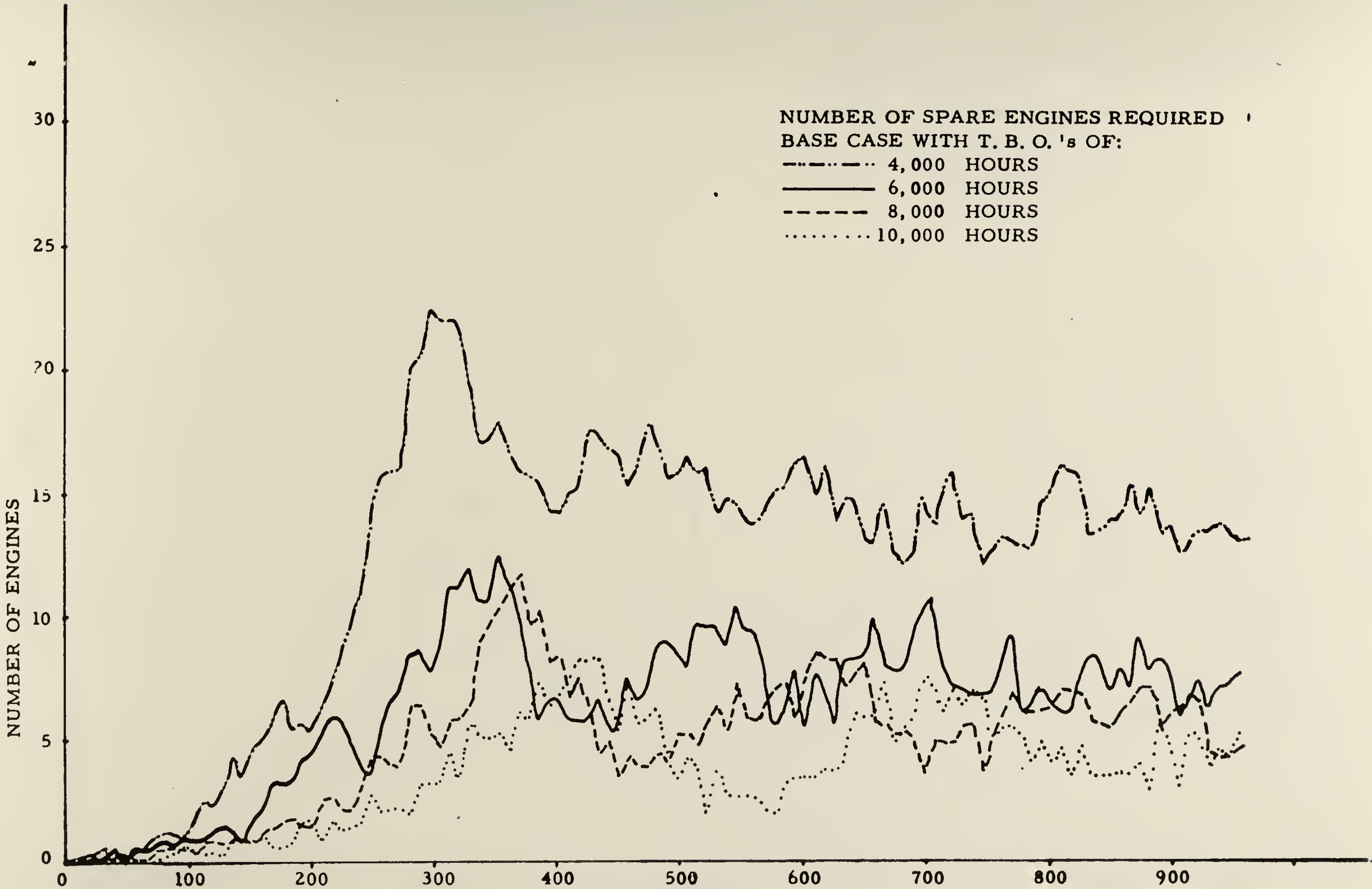
EFFECT OF RANDOM NUMBER CHANGE
FIGURE 5

The global maximum near week 300 appears to be caused by overlaping engine requirements. The first ships launched require engines for their second overhaul at the same time the last ships require engines for their first overhaul. As time progresses past F.Y. 1983 (week 400), the maximum and minimum requirements become less extreme due to the effects of the random variables in the system.

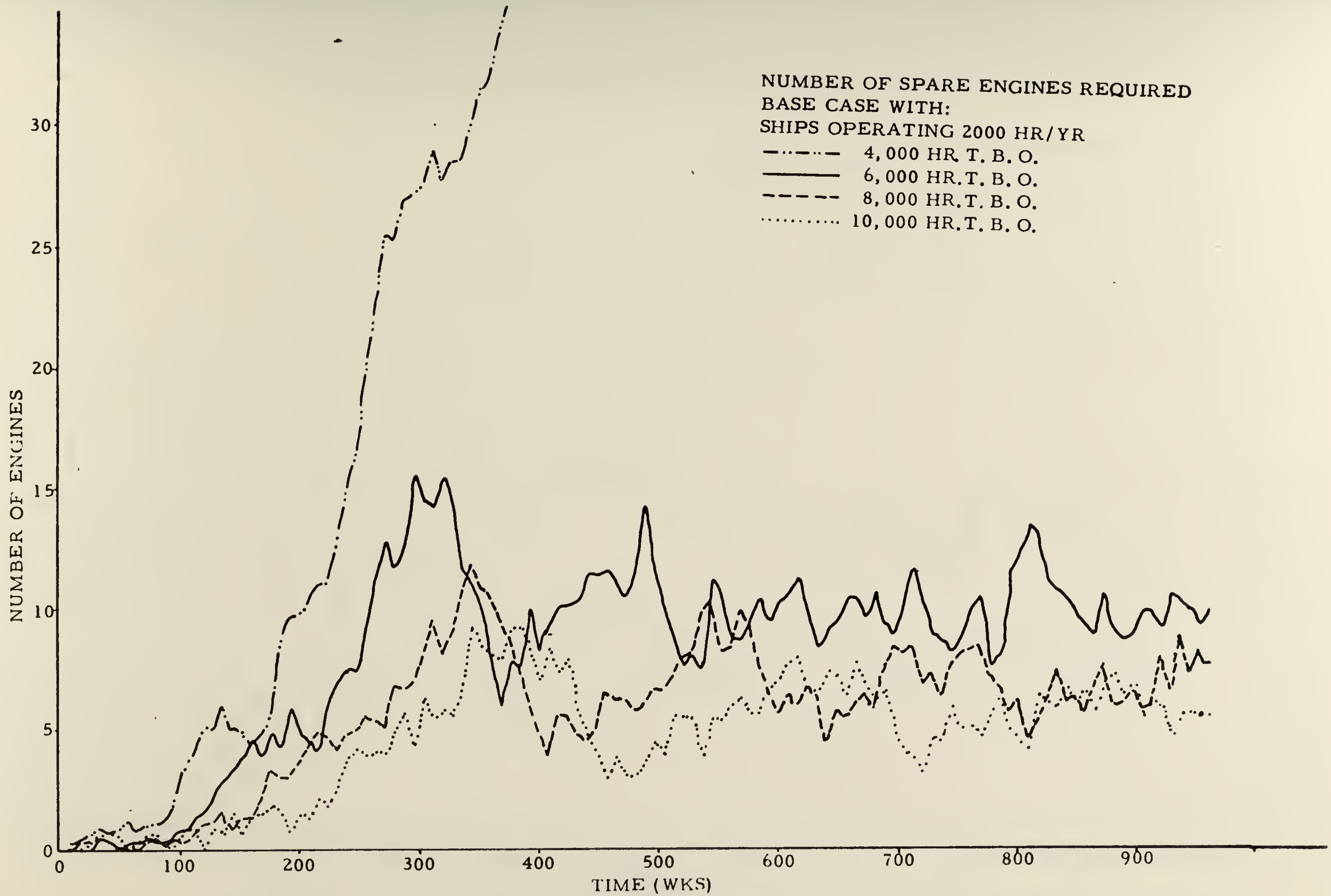
C. EFFECT OF CONSTANT TBO'S

The first variable investigated was the time between overhauls. Figure 6 illustrates the effect on 99% upper confidence limits of varying TBO over the values of 4,000, 6,000, 8,000 and 10,000 hours in the case where ships operate in a manner similar to present day destroyers. As the TBO increases, the number of engines required decreases and the time at which the maximum demand occurs is later. If the TBO is as short as 4,000 hours, the number of spare engines needed is significantly increased. The maximum is ten engines greater than with a 6,000 hour TBO.

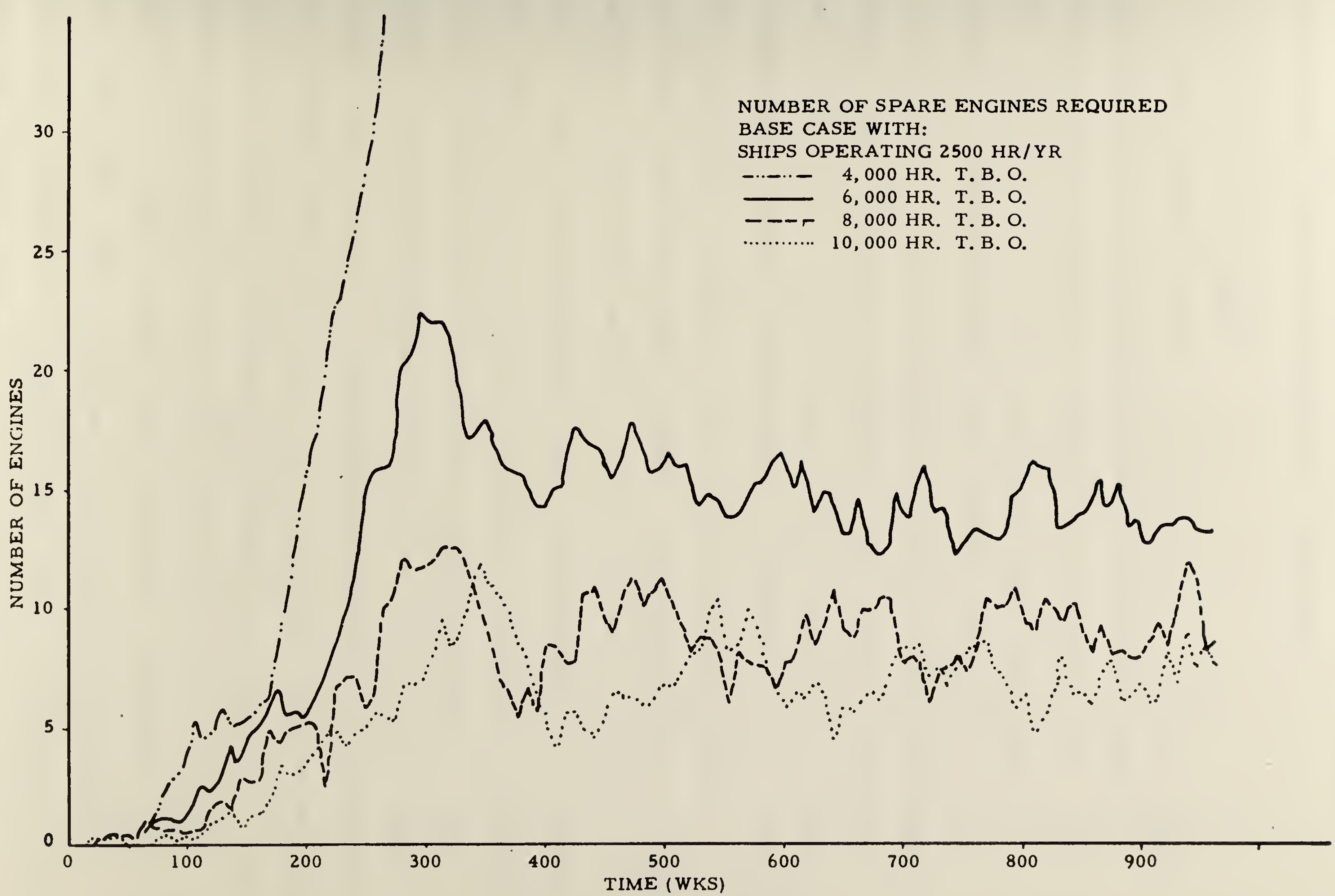
The effects of the same four TBOs were investigated in the cases of ships operating 2,000 and 2,500 hours per year (Figs. 7 and 8). As expected, increasing TBO decreased the number of spare engines required. If the engines are operated 2,000 or more hours per year and TBO is 4,000 hours, the rework facility becomes saturated and can not overhaul engines as fast as they are demanded.



EFFECT OF T. B. O. CHANGE
FIGURE 6



EFFECT OF T. B. O. CHANGE
FIGURE 7

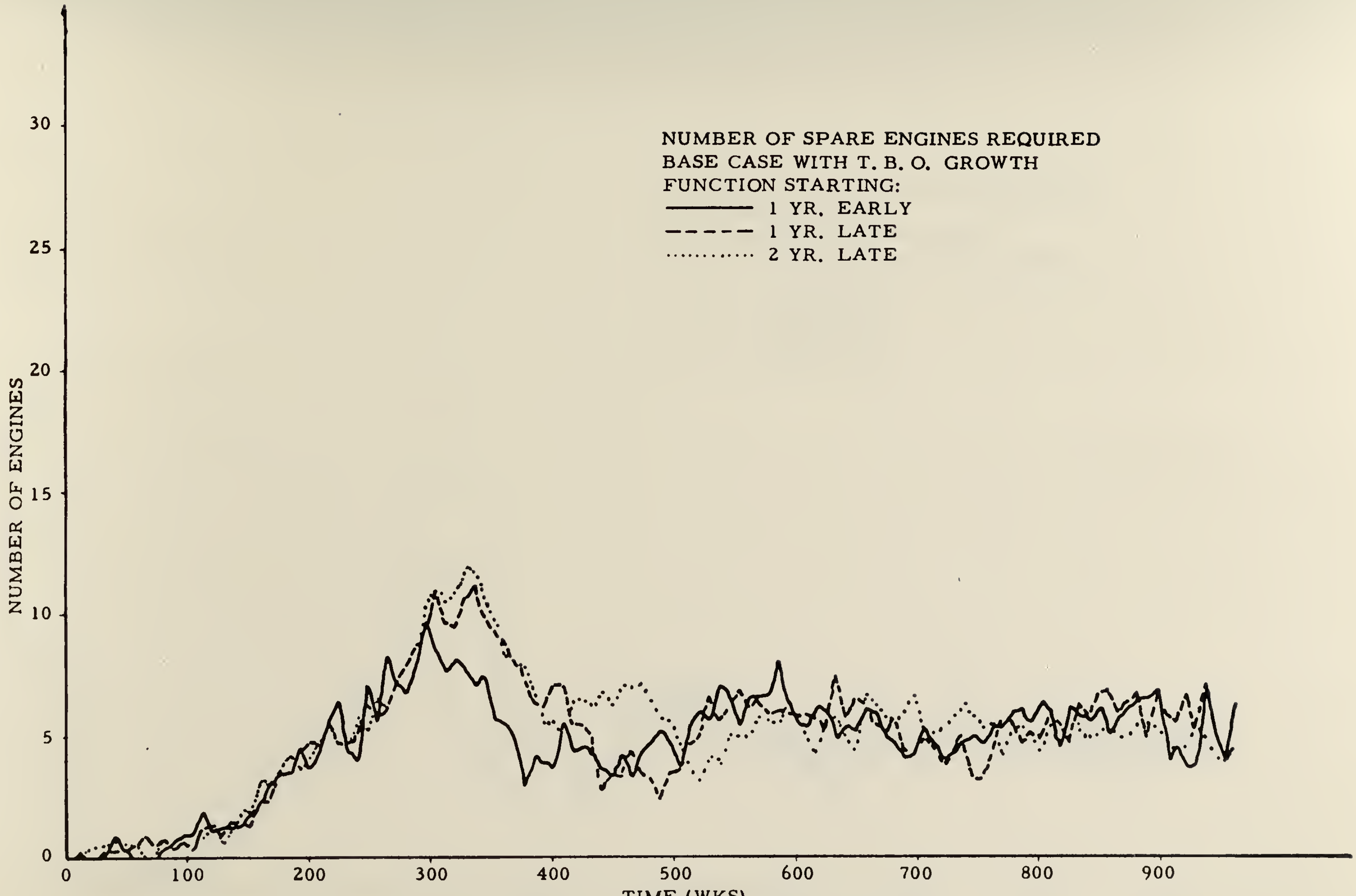


EFFECT OF T. B. O. CHANGE
FIGURE 8

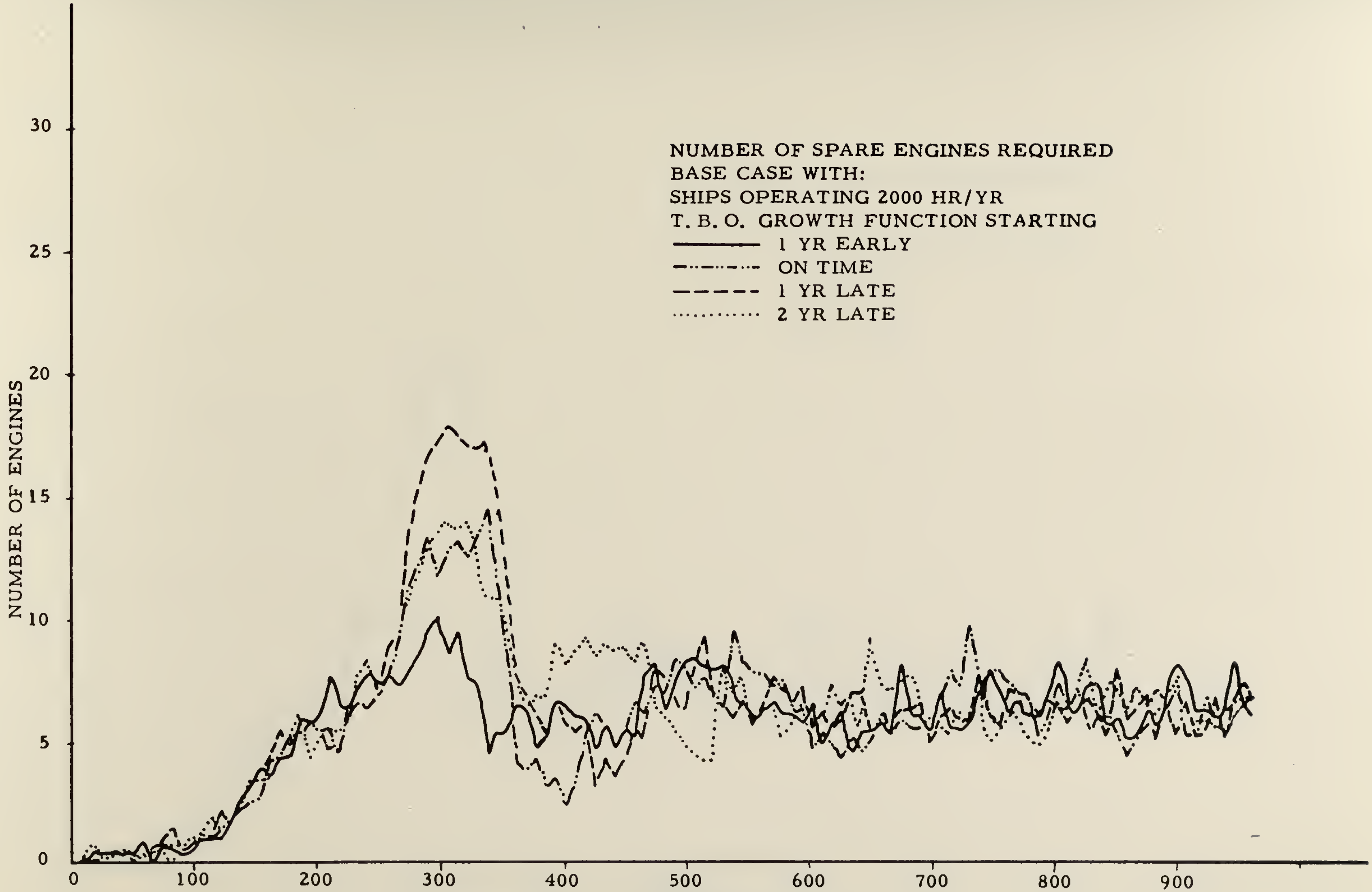
This condition exists even beyond the time when engine requirements should be expected to decrease.

D. EFFECT OF TBO GROWTH

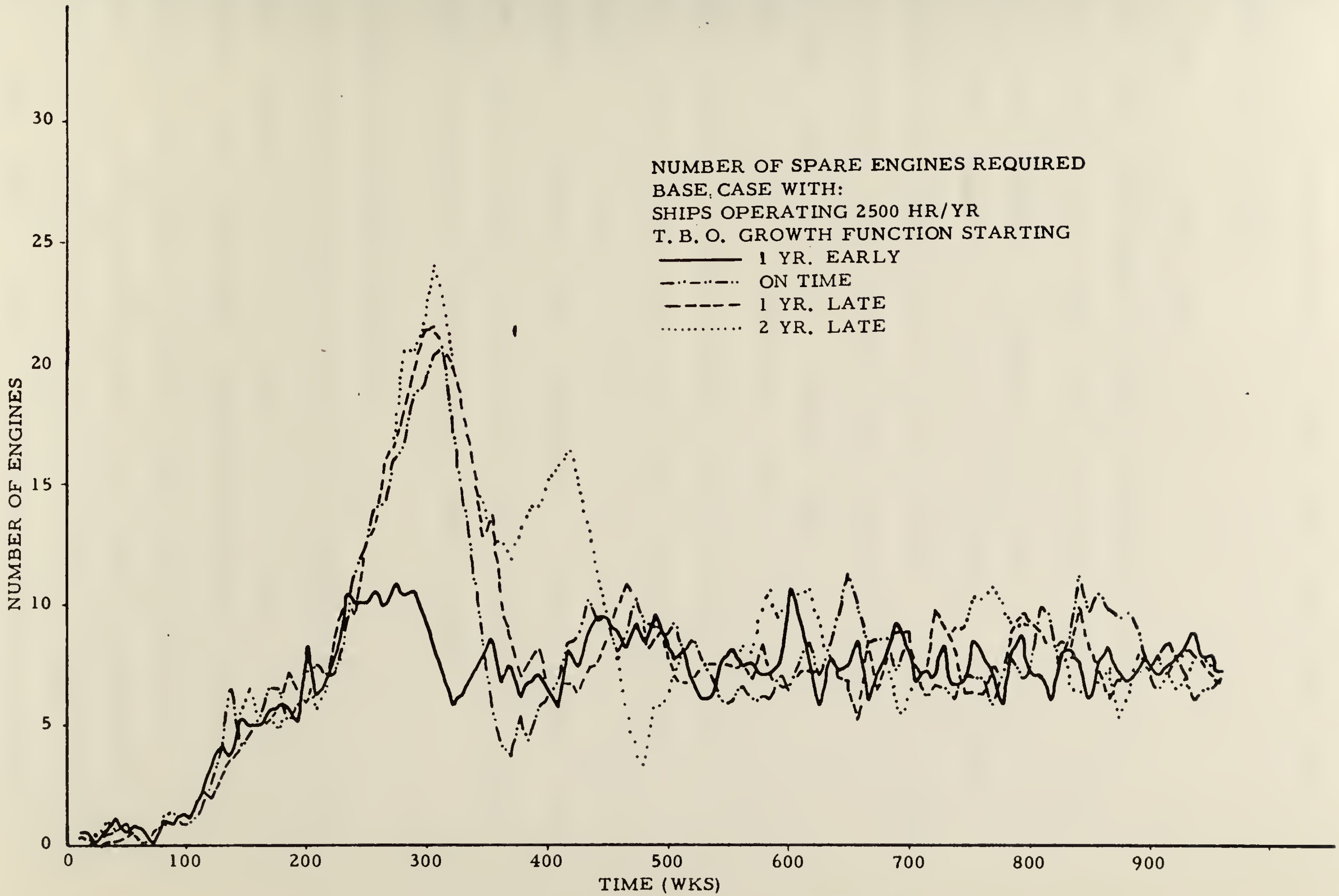
A TBO growth function is incorporated in the base case. This function is considered to be a reasonable guess of how TBO can be expected to increase with system life. The base case growth function and three others are shown in Figure 2. These functions were used to modify the current, 2,000 hour and 2,500 hour yearly operating time simulations. Results are presented in Figures 9, 10, and 11. Since the base case results fell between the other results in Figure 9, they were omitted for reasons of clarity. In the case of ships operating as they do now, the various TBO growth functions have very little effect. The difference in global maxima is only three engines. It can be seen in Figures 10 and 11 that, at an increased tempo of operations, a significant reduction in the number of engines required is achieved if the slightly better TBO growth rate is realized. This growth rate (TBO increases starting one year earlier than in base case) results in reductions of five and ten engines at 2,000 and 2,500 hours per year operating rates respectively. There is, however, an unexpected anomaly in Figure 10. The global maximum for the one year late growth rate case is almost four engines higher than expected. This was due to the higher than usual variance between observations near week 300. Another ten runs were made with a different random number seed and results almost coincident with the



EFFECT OF T. B. O. FUNCTION CHANGE
FIGURE 9



EFFECT OF T. B. O. FUNCTION CHANGE
FIGURE 10



EFFECT OF T. B. O. FUNCTION CHANGE
FIGURE 11

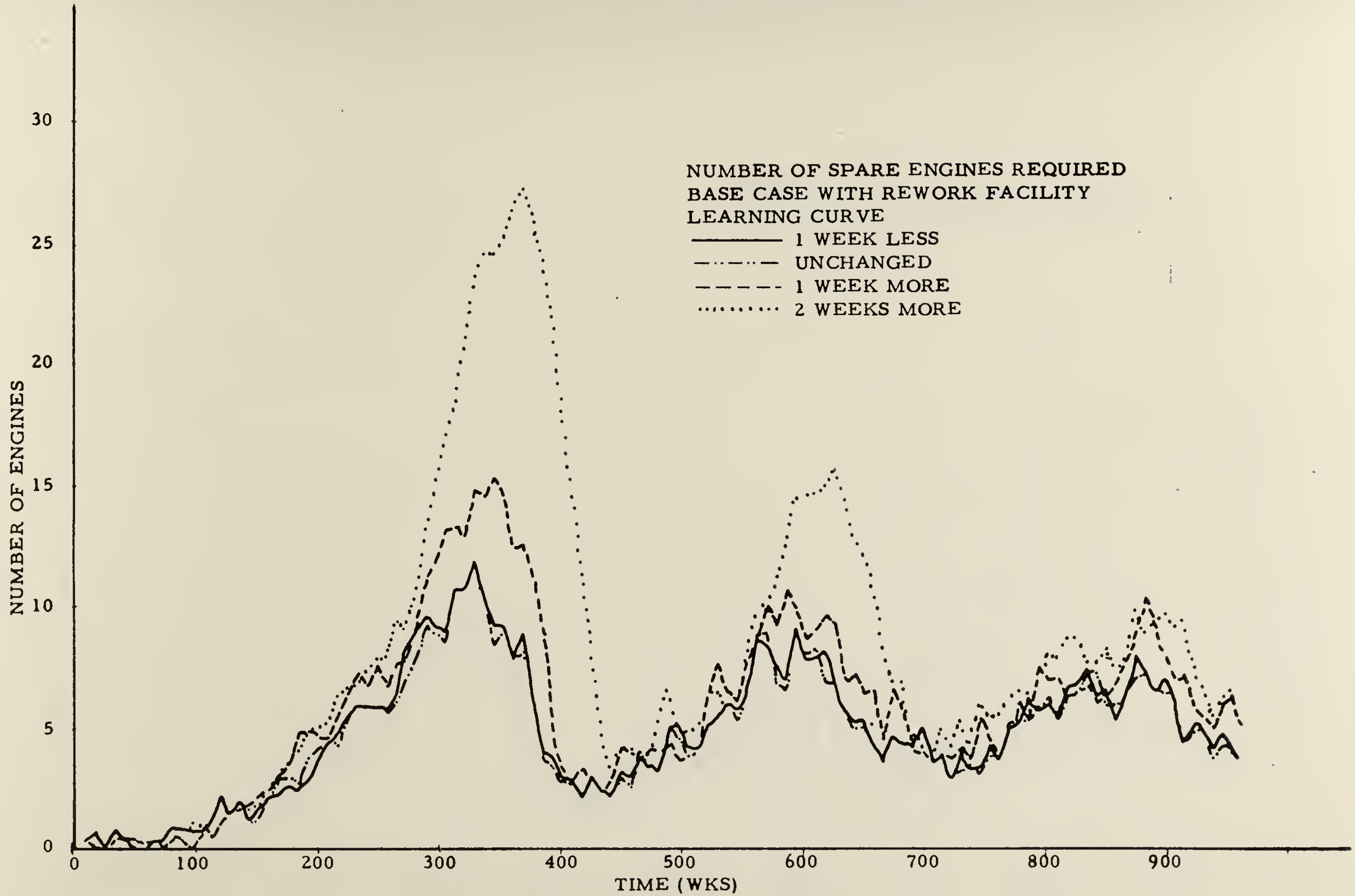
"on time" TBO growth function in Figure 10 were observed. There were no other cases in this study where this phenomenon was observed.

E. EFFECT OF REWORK TIMES

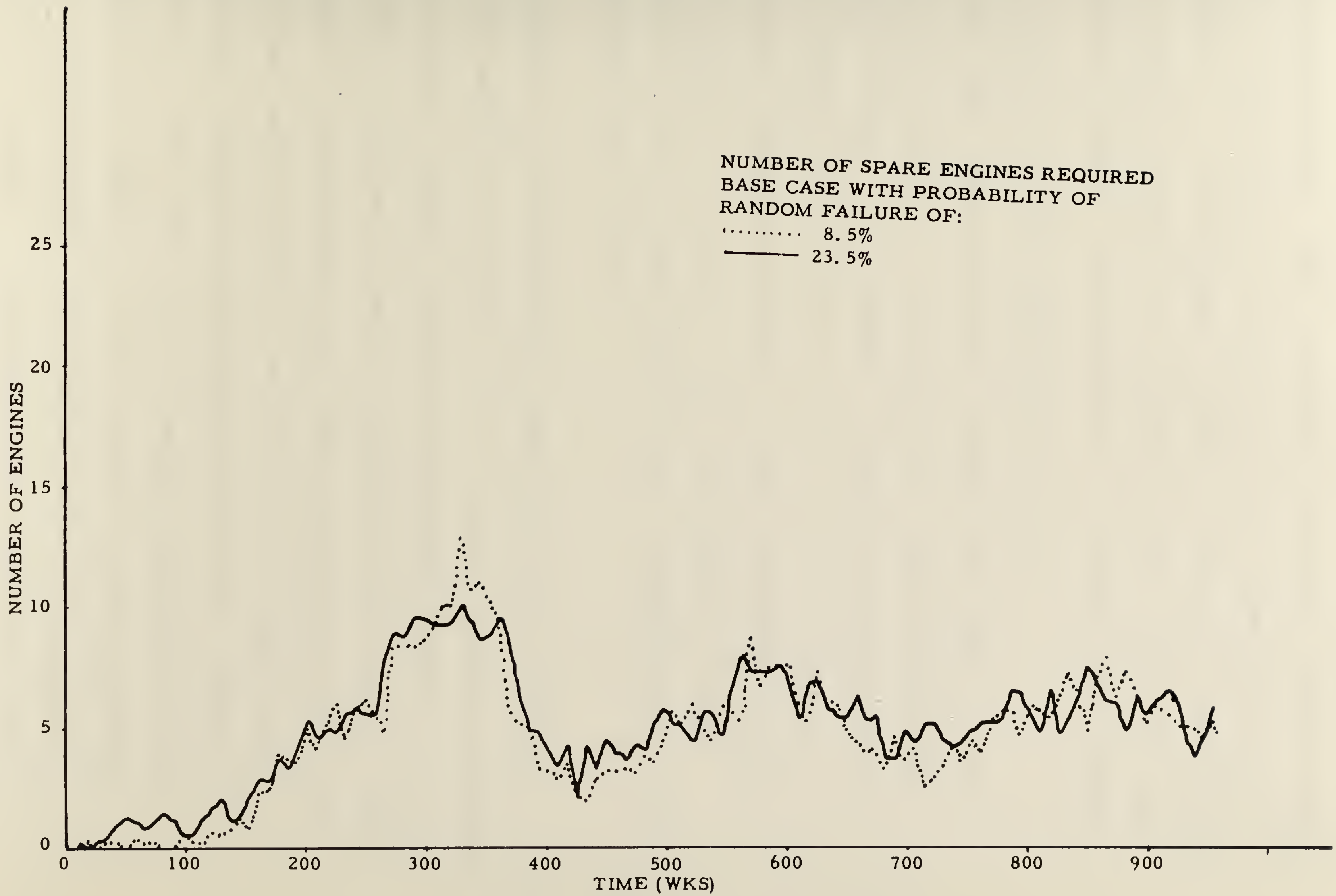
The base case rework time is assumed to be a step function (Fig. 3) in which the mean rework time is determined by the number of engines which have passed through the overhaul facility. Figure 12 illustrates the effect of varying the magnitude of this function. It can be seen that if rework time is taken as in the base case or one week less, the results are almost identical. When the overhaul time was one week more than in the base case, the maximum number of spare engines needed increased by three. When it was two weeks more, the spare engine maximum requirements increased by fifteen. This result was obtained utilizing a facility with a capacity of four engines. It is felt that a larger rework facility would significantly reduce the effect of these longer rework times.

F. EFFECT OF RANDOM FAILURES

The simulation was run with the probability of random failure changed to .085, .185, and .235 from the base case value of .135. There was little difference in results, therefore only the two extreme cases were plotted in Figure 13. It can be seen that the model is relatively insensitive to changes of the probability of random failure in the range .085 to .235. The maximum number of spare



EFFECT OF R. W. TIME FUNCTION CHANGE
FIGURE 12



EFFECT OF RANDOM FAILURE CHANGE

FIGURE 13

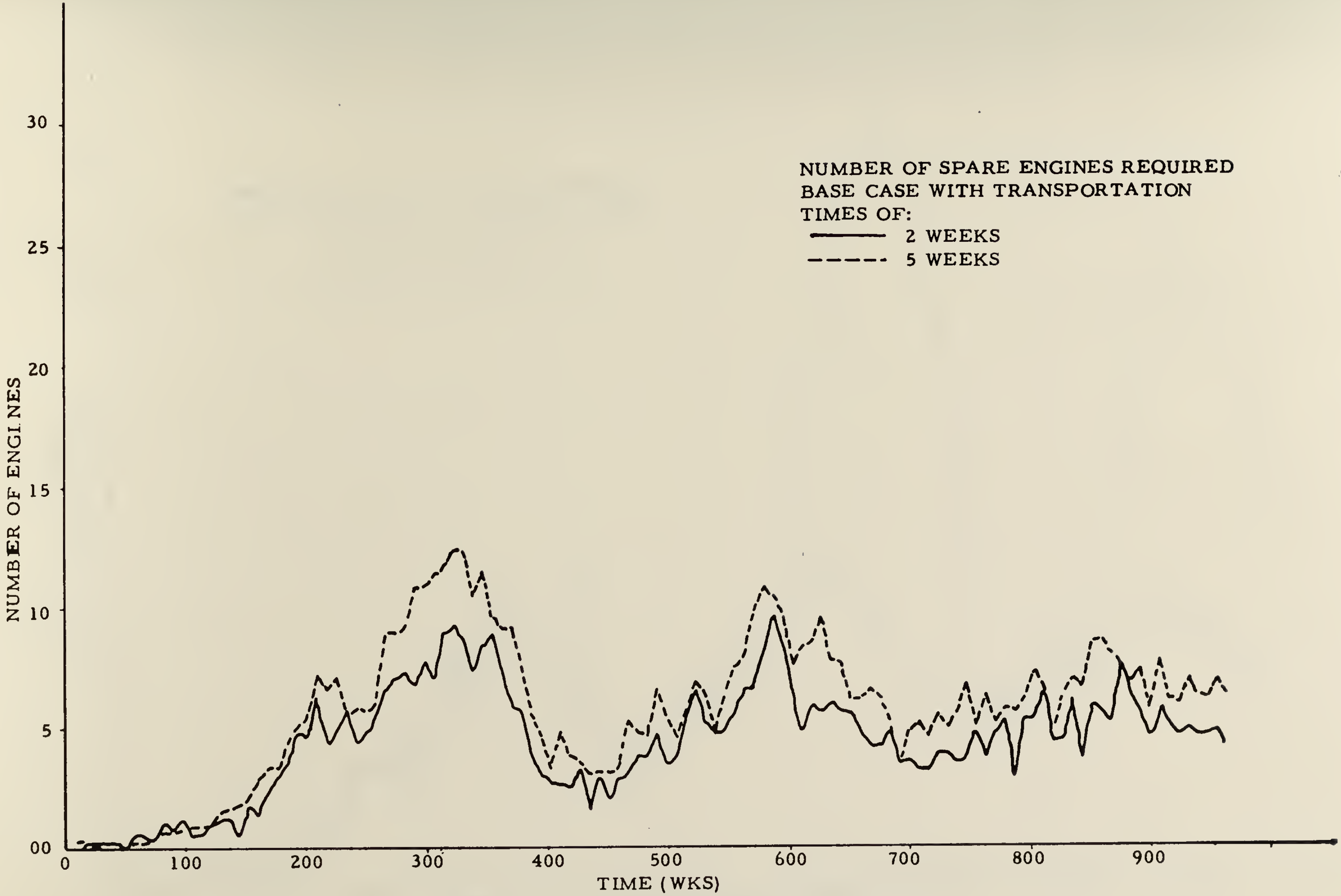
engines required actually decreases as more random failures are encountered. This is because the global maximum occurs when a large number of ships arrive for scheduled engine overhaul in a short period of time. Increasing random failures causes engines to fail prior to this time, thus fewer scheduled changes are required at the time of peak demand.

G. EFFECT OF SYSTEM TRANSPORTATION TIME

The base case with mean transportation time of three weeks was compared to runs made with times of two, four and five weeks. As expected, increasing transportation time increases the number of spare engines required. Since the increases were small, only the extreme values were plotted in Figure 14. The difference in global maxima for the two week and five week transportation time cases was three engines.

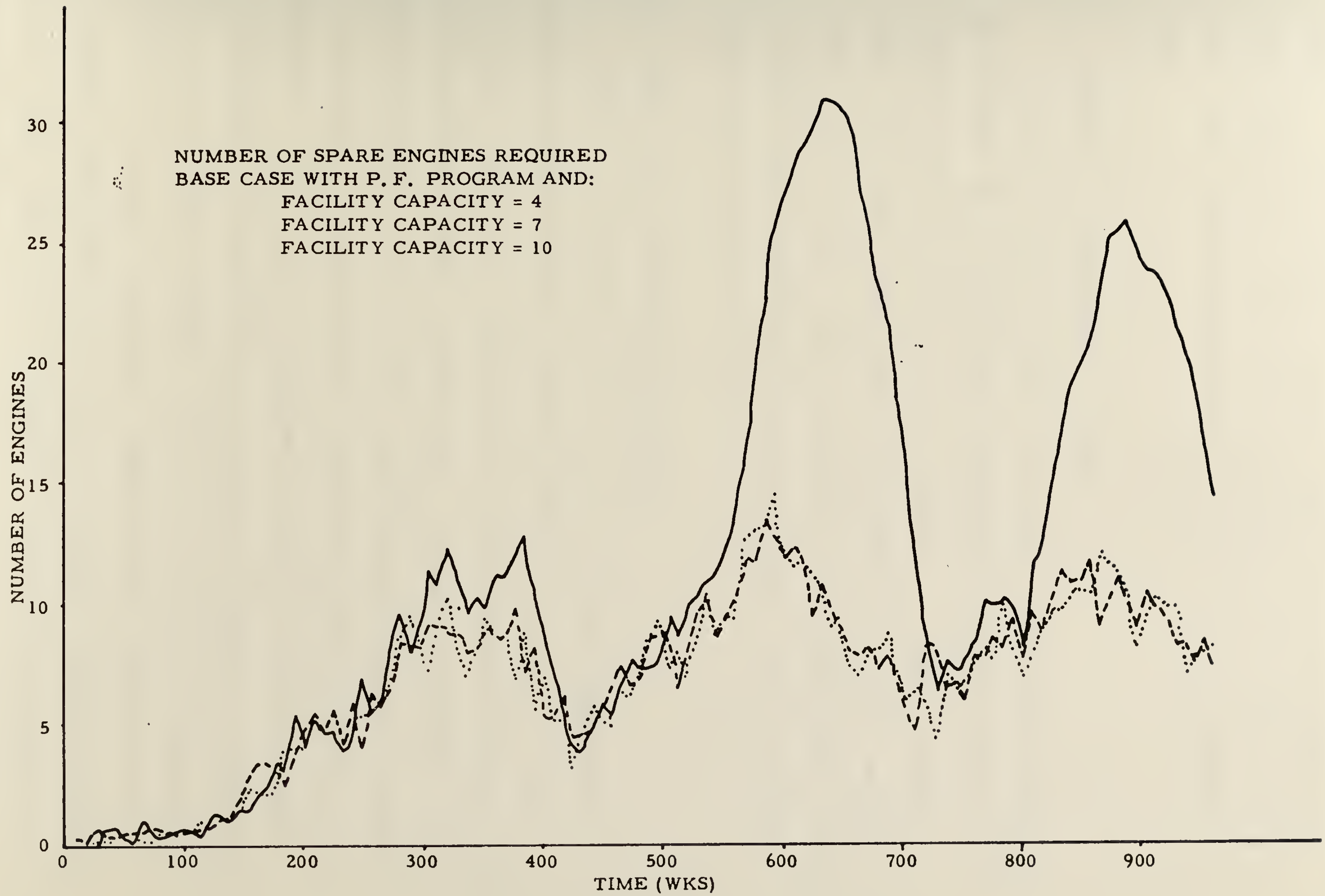
H. EFFECT OF PF PROGRAM AND REWORK FACILITY CAPACITIES

The effect of including the PF program in the simulation is to cause a global maximum of thirty one engines to occur at the six hundredth week of system life (F.Y. 1987). This maximum is large because the rework facility becomes saturated and cannot overhaul enough engines to satisfy the additional demand imposed by the PF engines. Figure 15 shows that this effect may be largely eliminated by increasing the capacity of the facility to seven engines. This increase reduces the maximum number of engines required by sixteen. A facility with a capacity of ten



EFFECT OF TRANSPORTATION TIME CHANGE

FIGURE 14



FACILITY EFFECTS WITH P. F. PROGRAM
FIGURE 15

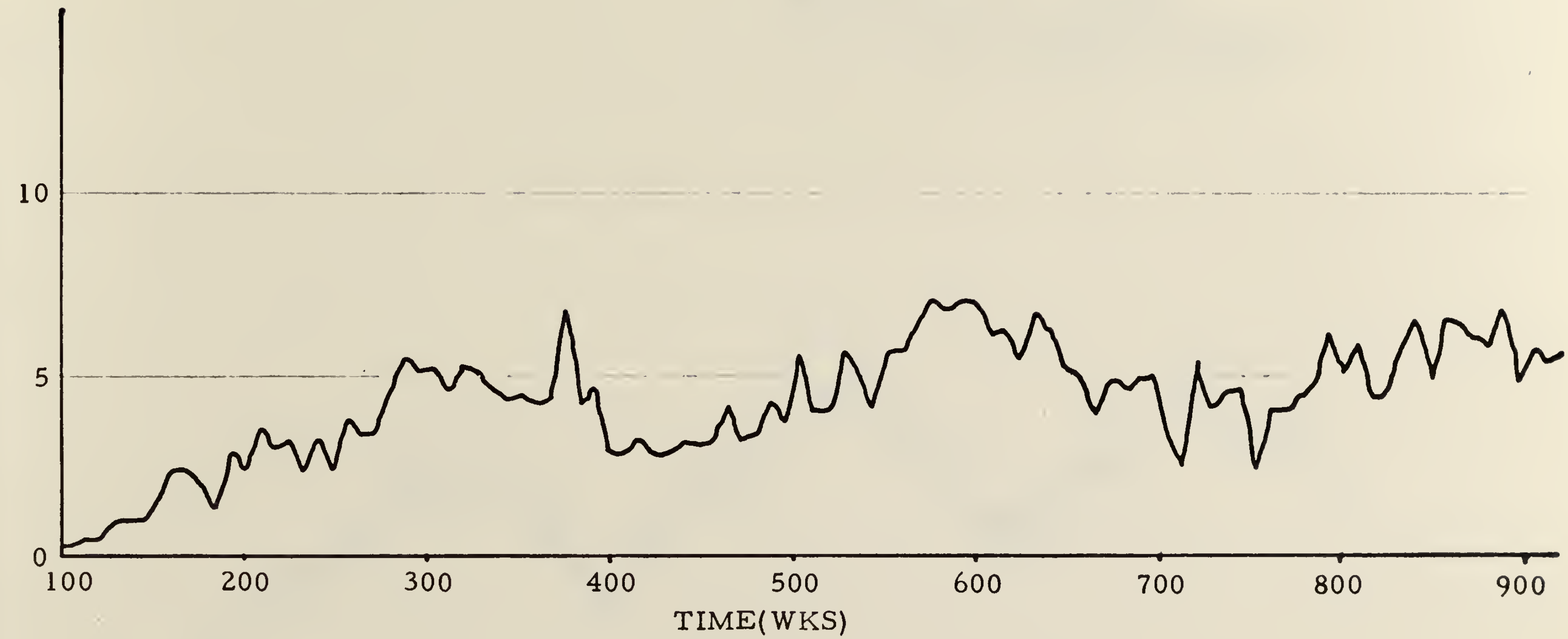
engines offers no substantial additional savings of spare engines. The reason for this can be seen in Figure 16 which shows that mean rework facility load (99% U.C.L.) never went above seven engines with a facility capacity of ten.

I. EFFECT OF MANAGEMENT OPTION

Figures 17 and 18 show the effect of allowing engines to operate up to 10% beyond scheduled overhaul time if the rework facility load is four engines. It can be seen (Fig. 17) that if the facility capacity is seven engines, this policy offers little advantage. A significant saving of eight spare engines is realized (Fig. 18) if a small four engine capacity facility is used.

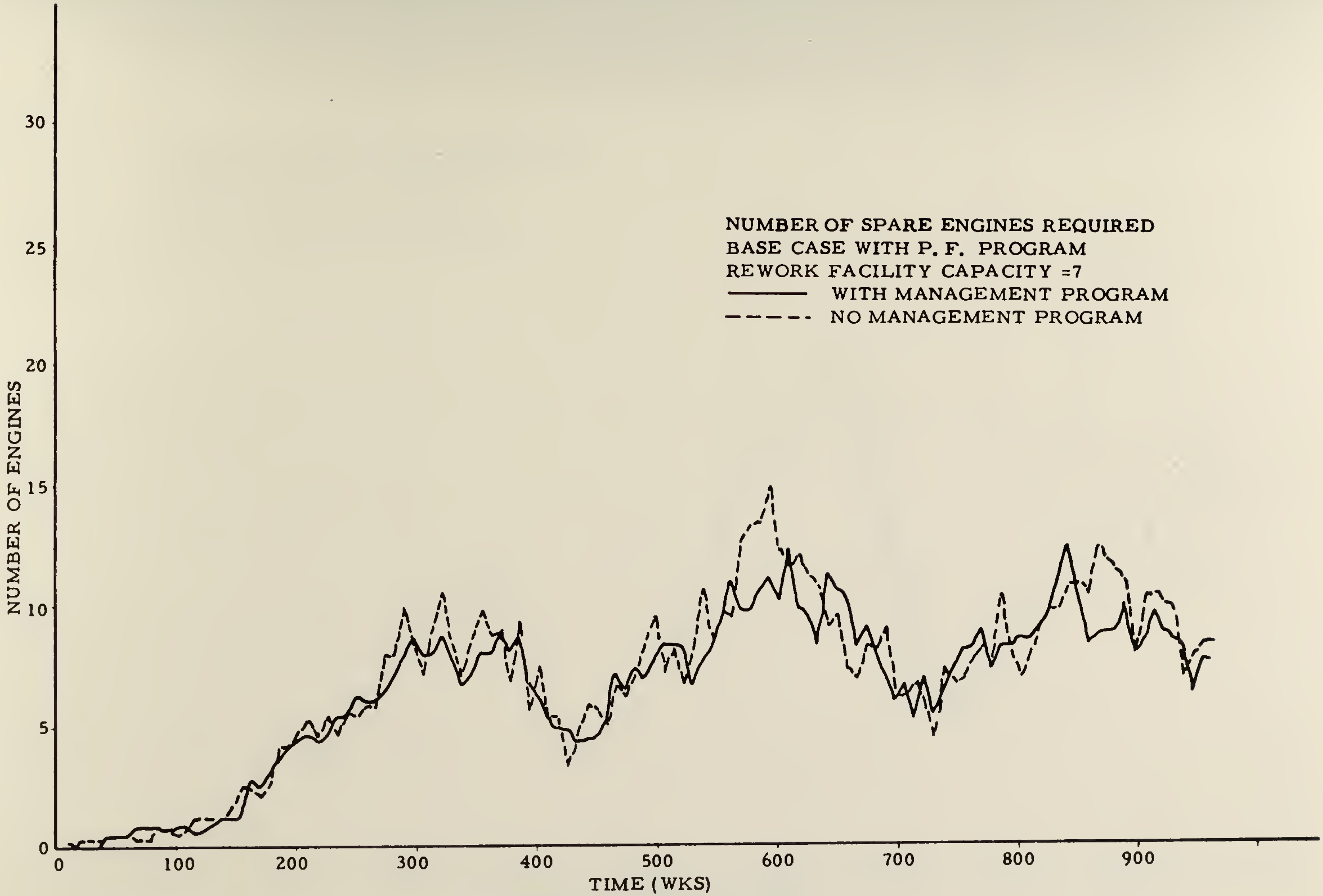
J. BASE CASE ENGINE REQUIREMENTS

Table 1 shows the fiscal years in which additional engines were required for the DD 963 program and their relative costs as a function of time between overhauls and the operating tempo of the ships. These are results when the simulation is run with a sufficient number of engines in the pool to preclude not having one available when demanded. The figures in Tables I and II, are the annual incremental increases of the number of engines needed from the pool to meet demand. These figures are 95% upper confidence limit of the mean. Rework time, percent early failure, transportation time, and rework facility capacity of the base case were utilized in all runs tabulated in Tables I and II.

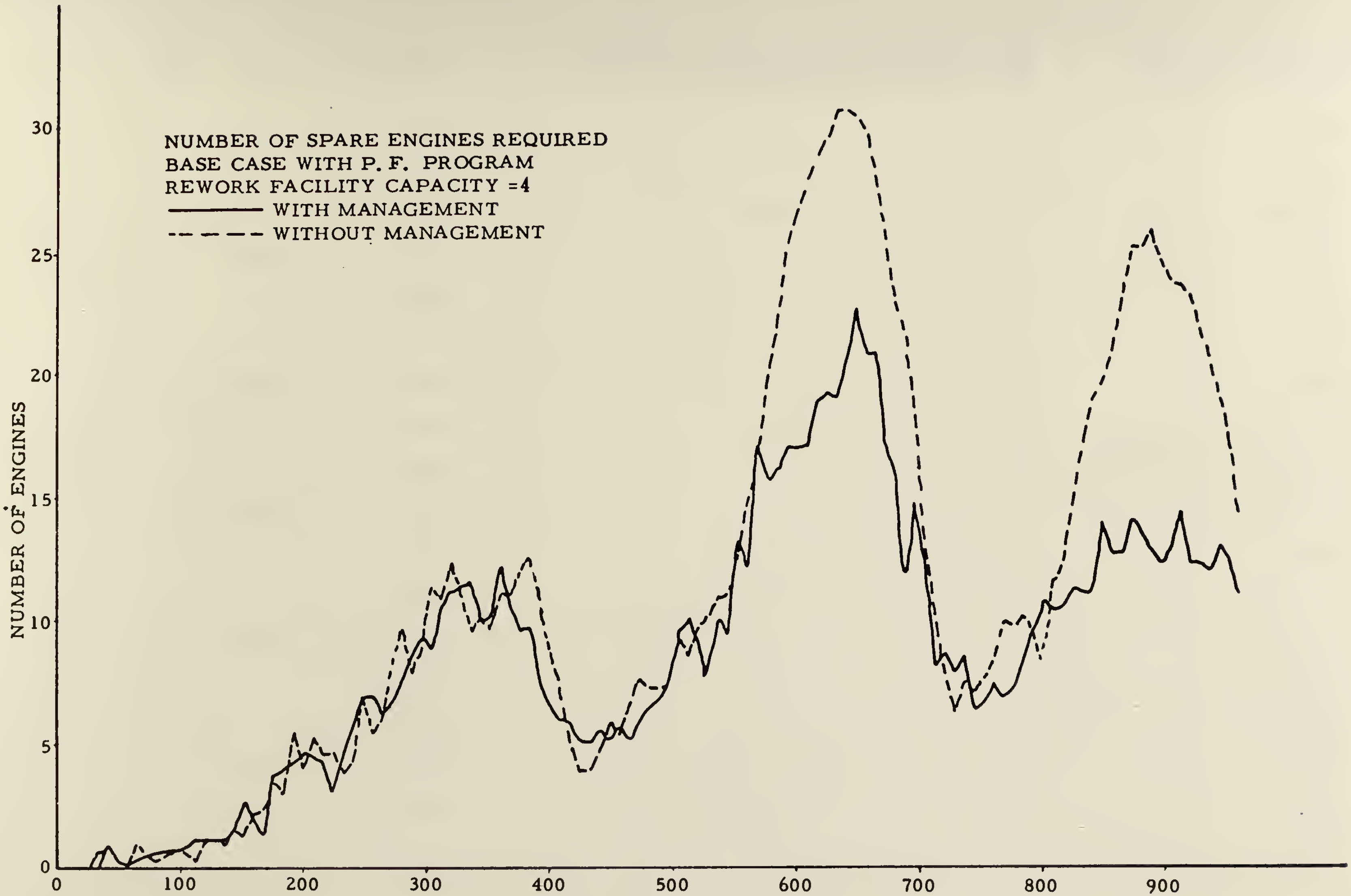


99% U. C. L. ON MEAN NUMBER OF ENGINES IN THE REWORK FACILITY

FIGURE 16



MANAGEMENT POLICY EFFECTS
FIGURE 17



MANAGEMENT POLICY EFFECTS
FIGURE 18

RUN NUMBER	TBO	OPERATING TEMPO	ENGINE REQUIREMENTS (BY FISCAL YEAR) 75	76	77	78	79	80	81	82	83	84	TOTAL ENGINES	TOTAL COST ($000,000)
1	4,000	1650	2	3	2	4	9						20	23.92
2		2000	2	1	3	4	12	6	5	7	5	59*	100	88.63
3		2500	1	4	1	11	19	13	20	17	14	1	101	109.99
4	6,000	1650	1		1	3	2	4	1				12	14.18
5		2000	1		4	1	6	3					15	17.74
6		2500	2	3	2	4	9						20	23.92
7	8,000	1650	1		1	1	1	2	5				11	12.48
8		2000	1		1	2	2	3	2				11	12.91
9		2500	1	1	1	2	5	2	1				13	15.61
10	9,000	1650	1		1		2	2	3				9	10.23
11		2000	1		1	2	2	2	1				9	10.59
12		2500	1		1	1	3	1	5	1			13	15.18
13	10,000	1650	1		1	1	2	1	2				8	9.13
14		2000	1		1		2	2	3				9	10.44
15		2500	1		1	2	2	3	2				11	12.91
16	12,000	1650	1		1		1	1	2	1	1		8	8.72
17		2000	1		1	1	2	2	2				9	9.90
18		2500	1		1	1	1	2	5				11	12.48

*Thru 1994

ENGINE REQUIREMENTS AT VARIOUS TBO'S AND OPERATING TEMPOS

TABLE I

RUN NUMBER	TBO	OPERATING TEMPO	ENGINE REQUIREMENTS (BY FISCAL YEAR)										TOTAL ENGINES	TOTAL COST ($000,000)
			75	76	77	78	79	80	81	82	83	84		
19	BASE	1650	1		2	2	3	2					10	12.12
20	CASE 1YR	2000	1		3	4		2					10	12.22
21	EARLY	2500	1	1	3	3	3						11	13.68
22	BASE	1650	1		2	2	1	4	1				11	13.19
23	CASE	2000	1		3	2	3	4	1				14	16.68
24		2500	1	1	5	1	6	6					19	23.88
25	BASE	1650	1		2	2	1	5					11	13.09
26	CASE 1YR	2000	1	1	3	1	3	8					17	20.12
27	LATE	2500	1	1	3	3	8	5					21	24.88
28	BASE	1650	1		3	1	2	4	2				13	15.25
29	CASE 2YR	2000	1		3	2	3	5					14	16.81
30	LATE	2500	1	1	5		7	9					23	27.27
31	BASE CASE	1650	2		1	3		4	1				11	13.22
32	TO	2000	2	3	1	5	1						12	14.47
33	12,000 HR	2500	1	1	3	2	8	5					20	24.96

ENGINE REQUIREMENTS AT VARIOUS TBO SCHEDULES AND OPERATING TEMPOS

TABLE II

Review of this data reveals that the engine requirements are relatively insensitive to time between overhauls when the TBO is 8,000 hours or more. The very large number of engines required for a TBO of 4,000 hours and operating levels of 2,000 and 2,500 hours per engine per year can attribute to the limited rework capacity as previously noted.

K. EFFECTS OF VARIOUS PURCHASE PLANS

After the general operating characteristics of the system were learned, several sample purchase plans were tested to determine expected engine weeks lost and the associated cost. In each purchase plan tested, it was assumed that the engines were paid for and delivered at the start of the fiscal year indicated. The purchase plans tested along with their results are shown in Table III. Engine weeks lost is a time weighted backorder measure of system effectiveness. It was assumed that a shortage of one engine for two weeks was equivalent to the shortage of two engines for one week in degredation of system effectiveness. All purchase plans were tested with the parameters of the base case.

As expected, purchase plans for more engines and earlier purchase dates resulted in lower numbers of engine weeks lost and correspondingly higher costs. Figure 19 is a plot of engine weeks lost versus total discounted costs. The numbers on Figure 19 refer to purchase plan numbers in Table III. The curve plotted on Figure 19 is an efficiency

PLAN NUMBER	PURCHASE PLAN (BY FISCAL YEAR) 74	75	76	77	78	79	80	81	83	TOTAL ENGINES	ENGINE WEEKS LOST	TOTAL COST
1		2	2	2	2					8	3088	10.78
2		2	2	2	2	1				9	2409	11.99
3		2	2	4	1					9	2409	12.17
4		1		1	2	2	3	1		10	2783	12.25
5		4	2	2	2					10	2026	13.66
6		2	2	3	3					10	1565	13.35
7		1		1	2	2	4	1		11	2229	13.40
8		1		2	2	1	4	1		11	2278	13.51
9		1		2	2	2	4			11	1289	13.62
10		1	1	2	2	2	3			11	1155	13.84
11	3	8								11	1175	15.88
12		1		2	2	2	4	1		12	1575	14.73
13		1	2	2	2	2	3			12	617	15.20
14		1	2	2	2	4	1			12	529	15.33
15		3	2	2	4	1				12	668	15.94
16		1	1	2	2	2	4	1		13	803	16.09
17		4	4	4	1					13	498	17.79
18		2	1	2	2	2	4	1		14	510	17.54
19		2	4	4	4					14	442	18.67
20		4	4	4	2					14	442	19.04
21		4	4	4	3					15	183	20.30
22		4	4	4	4					16	183	21.55
23		4	4	6	4					18	183	24.20
24		4	6	5	5					20	183	26.86
25		4	8	8	8	2				30	183	39.76
26	3	8	8	10	5					34	183	46.31
27	3	8	8	10	8					37	183	50.08

RESULTS OF PURCHASE PLAN TESTS

TABLE III

DOLLARS VERSUS ENGINE WEEKS LOST
TRADEOFFS

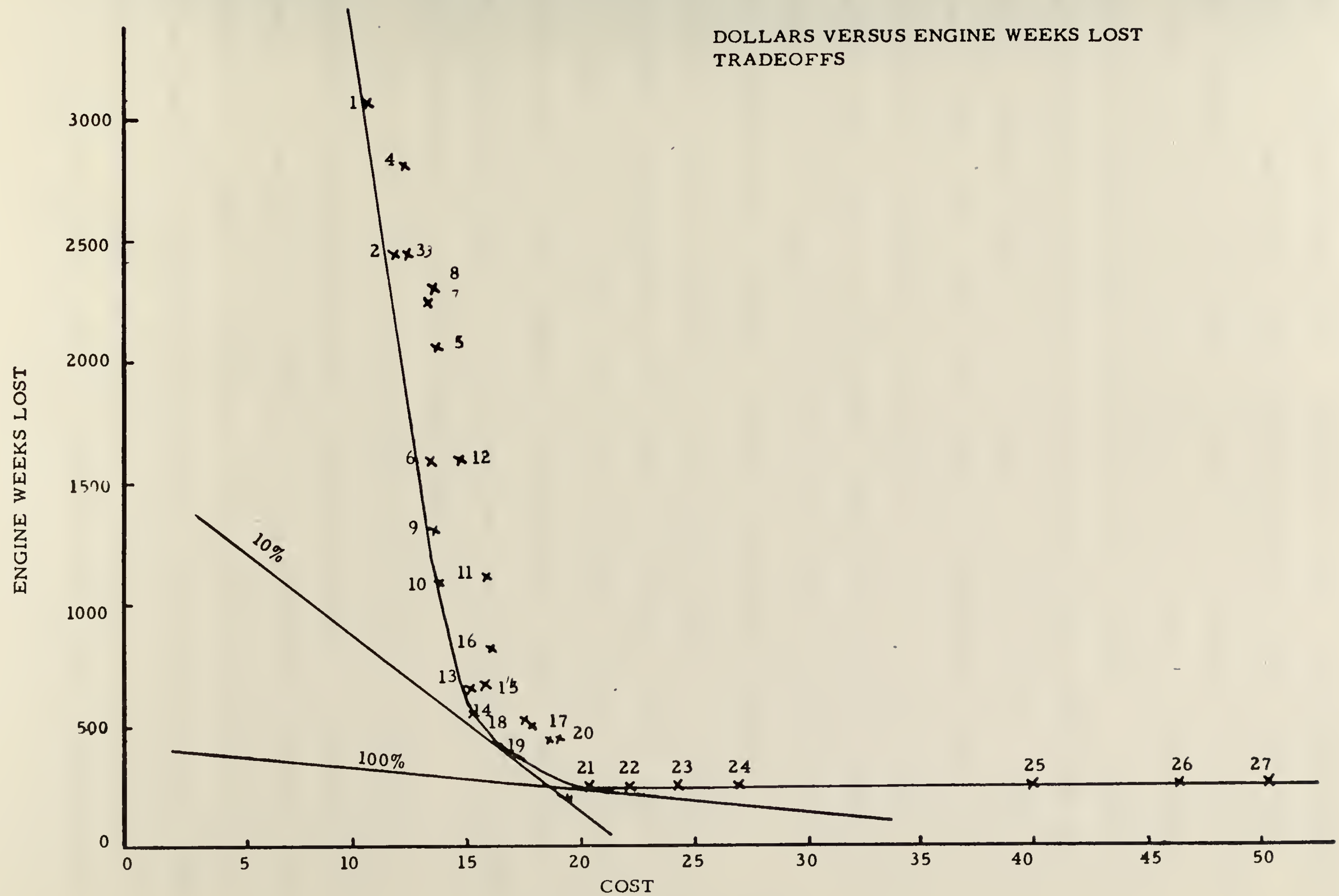


FIGURE 19

frontier for the system, i.e. each point on the curve represents the least cost purchase plan strategy for a given number of engine weeks lost. Figure 19 also illustrates which plans are dominated (more expected engine weeks lost for more dollare); for example, plan 16 is dominated by plan 15.

The slope of the two straight lines indicate the trade-off rate between engine weeks lost and dollars. A projected cost of $25,000 per day or $175,000 per ship week was used in the determination of the slope of these lines. The 10% line assumes the lack of one engine decreases a ship's capability to complete its mission by 10% and the 100% line assumes the lack of one engine causes the ship to lose all capability to complete its mission. Thus, in this case, the decision lies between the two points of tangency, roughly 12 to 15 engines in the rotable pool. The optimal purchase plan depends on the cost of having a ship without an engine for one week. Thus the optimal number of engines in the pool is that number of engines for which the cost of an additional engine is greater than the savings that result from reducing the engine weeks lost.

Also significant, is the fact that plans 21 through 27 resulted in increased costs but no decrease in the expected number of engine weeks lost. This implied that there were a sufficient number of engines in the pool to have one avialable whenever a demand was generated and that the only time the fleet was short an engine was during the time required to transport and install an engine which was a replacement

for an early failure. Engines for scheduled changes are assembled to be shipped sufficiently in advance to be available when the old engine is removed from the ship. Also implied is that there is no increase in pool size which would eliminate transportation and installation time loses for early failure engines.

Five purchase plans were tested to determine if increasing rework capacity in lieu of buying more engines would reduce the engine weeks lost. The result of the increased rework capacity is shown in Table IV. The results of four of the plans are plotted in Figure 20 with base case rework facility capacity indicated. Plans 21 and 22 resulted in no significant differences in engine weeks lost at any rework facility capacity. The faility capacity affected the engine weeks lost when a purchase plan with a lower number of engines was tested. This illustrates the existence of a cost tradeoff between rotable pool size and rework facility size. It was possible to obtain the same minimum number of engine weeks lost with plan 21 for 15 engines and a rework capacity of four, and plan 19 for 14 engines and a rework capacity of eight. The decision here would depend on the cost of adding an additional engine to the rotable pool and the cost of increasing rework facility capacity.

PLAN NUMBER	REWORK CAPACITY	PURCHASE PLAN (BY FISCAL YEAR) 75	76	77	78	79	80	81	82	TOTAL ENGINES	ENGINE WEEKS LOST	TOTAL INVENTORY COST ($000,000)
14	4	1	2	2	2	4	1			12	529	15.33
	5										383	
	6										320	
	7										240	
	8										240	
17	4	4	4	4	1					13	498	17.79
	5										250	
	6										216	
	8										174	
19	4	2	4	4	4					14	442	18.67
	6										320	
	8										174	
21	4	4	4	4	3					15	183	20.30
	6										187	
	8										174	
22	4	4	4	4	4					16	183	21.55
	6										193	
	8										187	

RESULTS OF PURCHASE PLANS TESTS WITH VARIOUS REWORK FACILITY CAPACITIES

TABLE IV

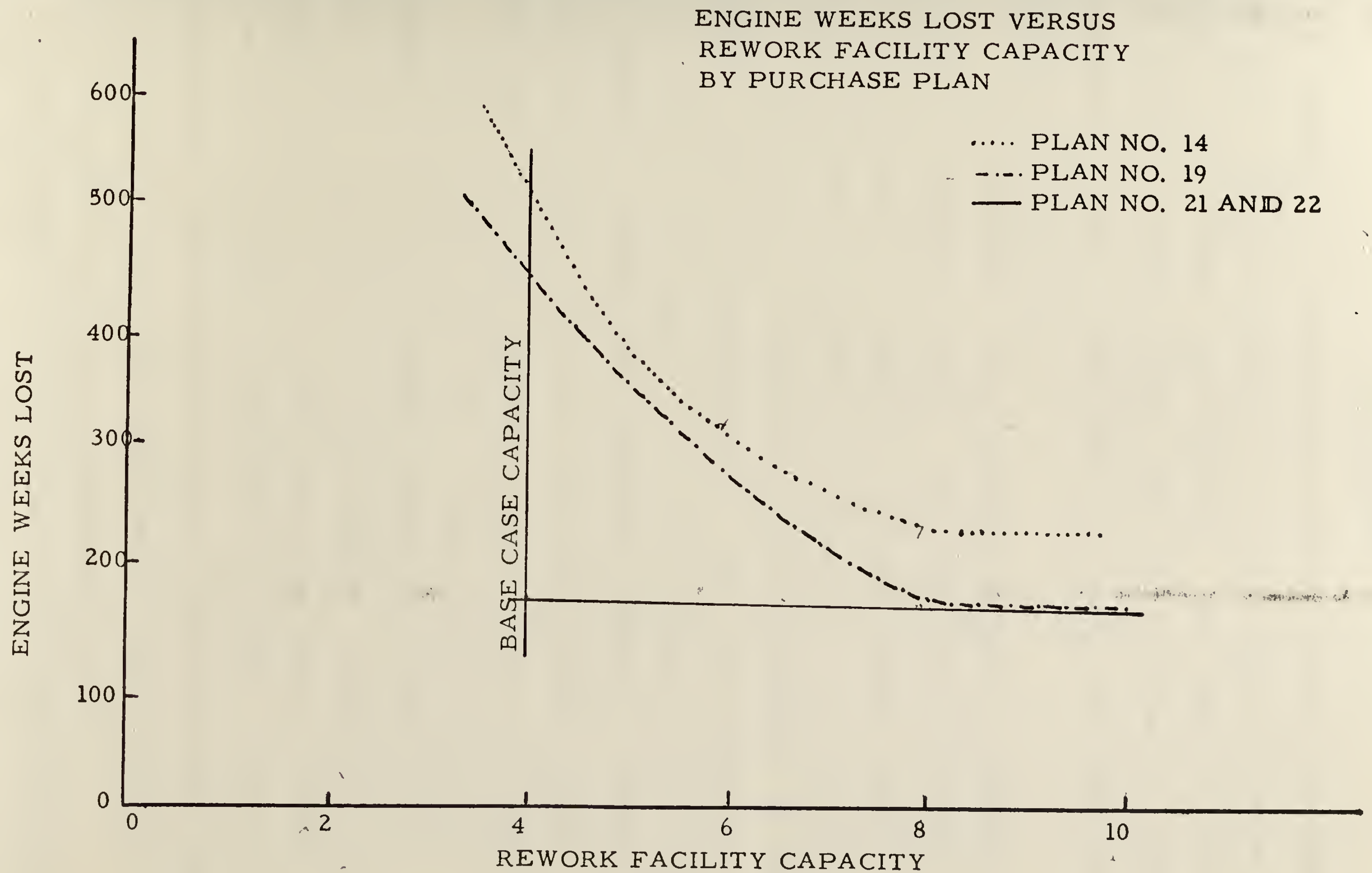

ENGINE WEEKS LOST VERSUS
REWORK FACILITY CAPACITY
BY PURCHASE PLAN
PLAN NO. 14
PLAN NO. 19
PLAN NO. 21 AND 22
BASE CASE CAPACITY
ENGINE WEEKS LOST
600
500
400
300
200
100
0
0
2
4
6
8
10
REWORK FACILITY CAPACITY

FIGURE 20

V. CONCLUSIONS

1. Rotable pool requirements are most heavily dependent upon rework facility capacity, i.e. that number of engines which can be in rework simultaneously. Any condition which will produce an engine removal rate from the fleet of about 40 engines per year is sufficient to saturate the facility (facility capacity=four).

In particular, the PF program requires 33 engines in the pool if capacity is four. This requirement decreases to 16 if the capacity is greater than seven engines. Little further improvement is observed for capacities larger than seven.

2. The effect of increasing operating schedule is comparable to that of decreasing TBO. Again, the engine removal rate will determine if facility capacity is sufficient. Any operation schedule/TBO combination yielding a removal rate of 40 engines a year will drive pool engine requirements above 20, other parameters held at base case levels.

3. TBO growth rates (Fig. 2) have little effect on rotable pool size with current operations. The best to worst case differential is three engines. Increasing the operating tempo to 2000 engine hours per year will result in an engine requirement differential of eight engines. If operating hour requirements increase to 2500 hours per year, then the best to worst case difference in TBO growth will yield a difference in engine requirements of 15.

4. Increasing mean rework time by two weeks across the entire learning curve will result in additional requirements

of 16 engines, whereas an average one week increase results in only four additional engines being required over the base case. Base case requirement are for 12 engines. A decrease of one week across the learning curve does not affect system requirements. This is due to the fact that the rework time is bounded below at 25 days and during the portion of time when the rework time decrease is effective, system load is light.

5. The percentage of operating engines failing randomly is not critical to the system in the range 8.5% to 23.5%.

6. System transit time is significant to the extent that one additional week in transit will require a rotable pool increase of about one engine.

7. Extensions of TBO by ten percent contingent on rework facility load levels have significant potential if the rework capacity is small (four engines). Extensions have little effect at the higher facility capacity levels.

8. For the base case assumptions with rework capacity variable, system effectiveness is optimized for a rework capacity of 7-8 engines and the purchase of 14-16 engines early in system life as rotable pool spares, depending somewhat on the cost of the rework facility.

VI. RECOMMENDATIONS

1. Acquire and analyze available cost/time data for probable transportation systems. Optimum system transit time can then be computed.

2. Acquire and analyze ship operating profiles to determine which overseas stock points are prime candidates for possible stockage for random failures. Once prime stockage locations have been identified, transportation cost/time data can be used to determine if overseas stocking should be used. Since most engine failures can be expected to occur while the ship is at sea, consideration should be given to the possibility that a spare engine can be transported to the installation point prior to the arrival of the ship. If this were done, prepositioning would not further reduce lost engine time.

3. Determine the effect of sets of engines arriving for rework simultaneously.

4. Determine cost of rework facility at various capacities to evaluate possible pool size/rework facility capacity tradeoffs.

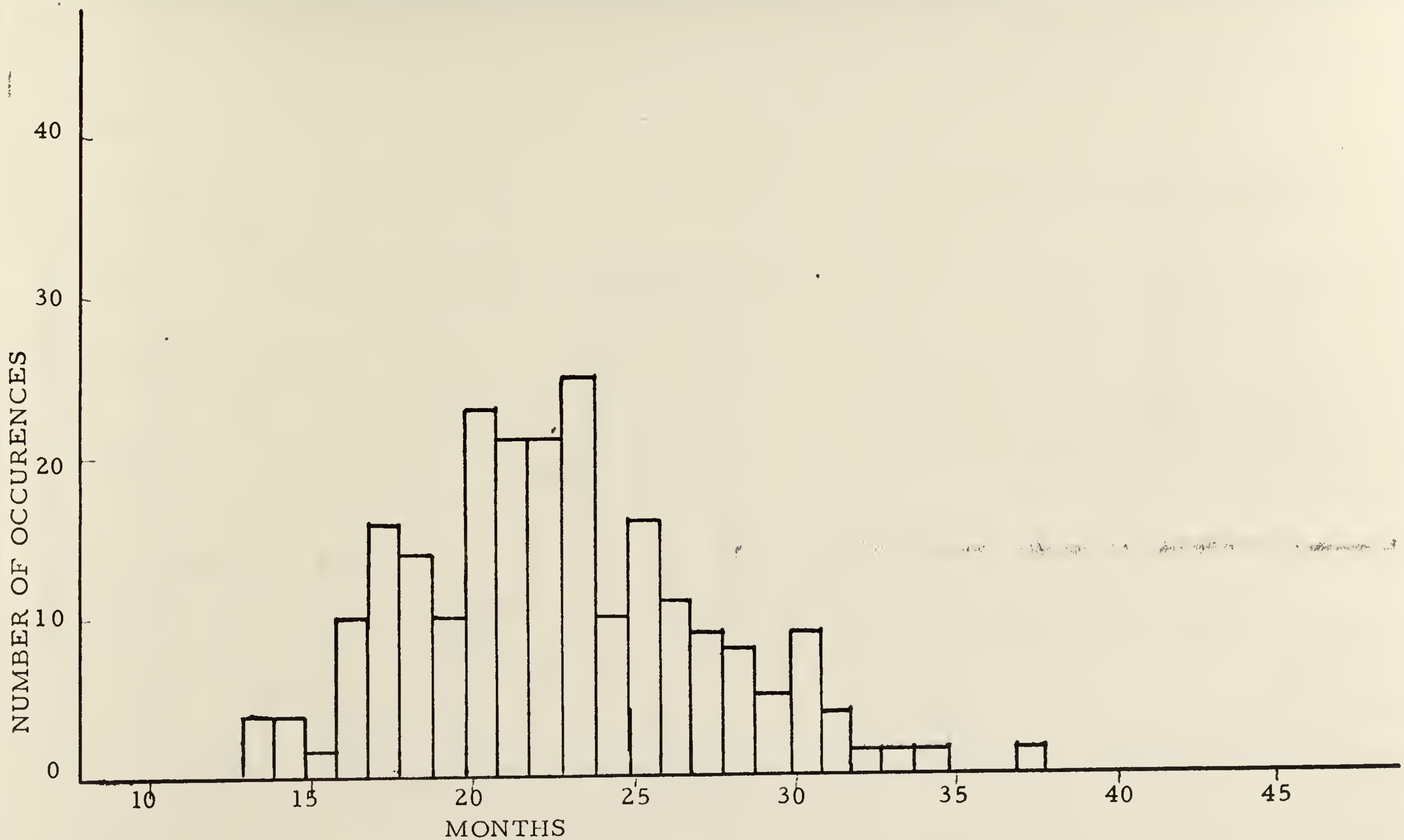
APPENDIX A

DISTRIBUTION OF TIME BETWEEN SCHEDULED OVERHAULS

Data on destroyer operations was obtained from the Navy Maintenance and Material Information System, Steaming, Operating, and Fuel Listing dated 20 August 1971 [Ref. 4], which lists the number of hours each destroyer type ship was underway each month from July 1965 through April 1971. It was assumed that the DD 963 class destroyers operating schedules will be similiar to the current schedules of a destroyer (DD), a guided missile destroyer (DDG), or a guided missile frigate (DLG). The monthly hours at sea were totaled for each ship until totals of 6,000, 9,000 and 12,000 hours at sea were accumulated to determine the number of calendar months it took to accumulate the specified number of hours. Linear interpolation was used to determine what poriton of the final month was required to reach the desired total number of hours.

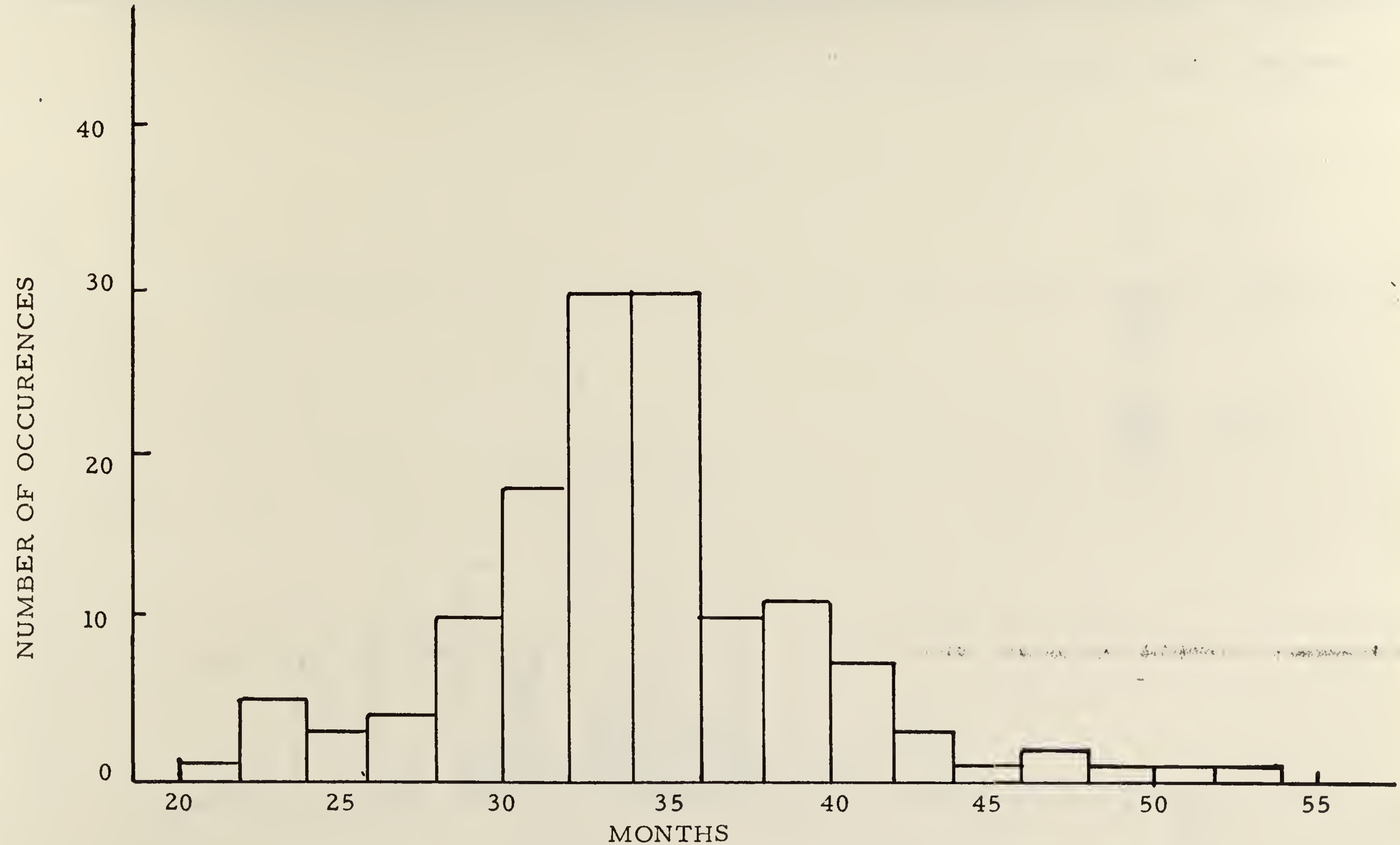
From these totals by ship, three histograms (Figs. A-1, A-2 and A-3) were drawn to determine the distribution of calendar months to reach a specified number of hours at sea.

Three least squares regressions were performed on the mean, maximum, and minimum times to accumulate 6, 9, and 12 thousand hours at sea to predict the calendar months required for a specified number of hours at sea. Figure A-4 shows the actual data points and the three linear regression lines. From Figure A-4 it was assumed that the



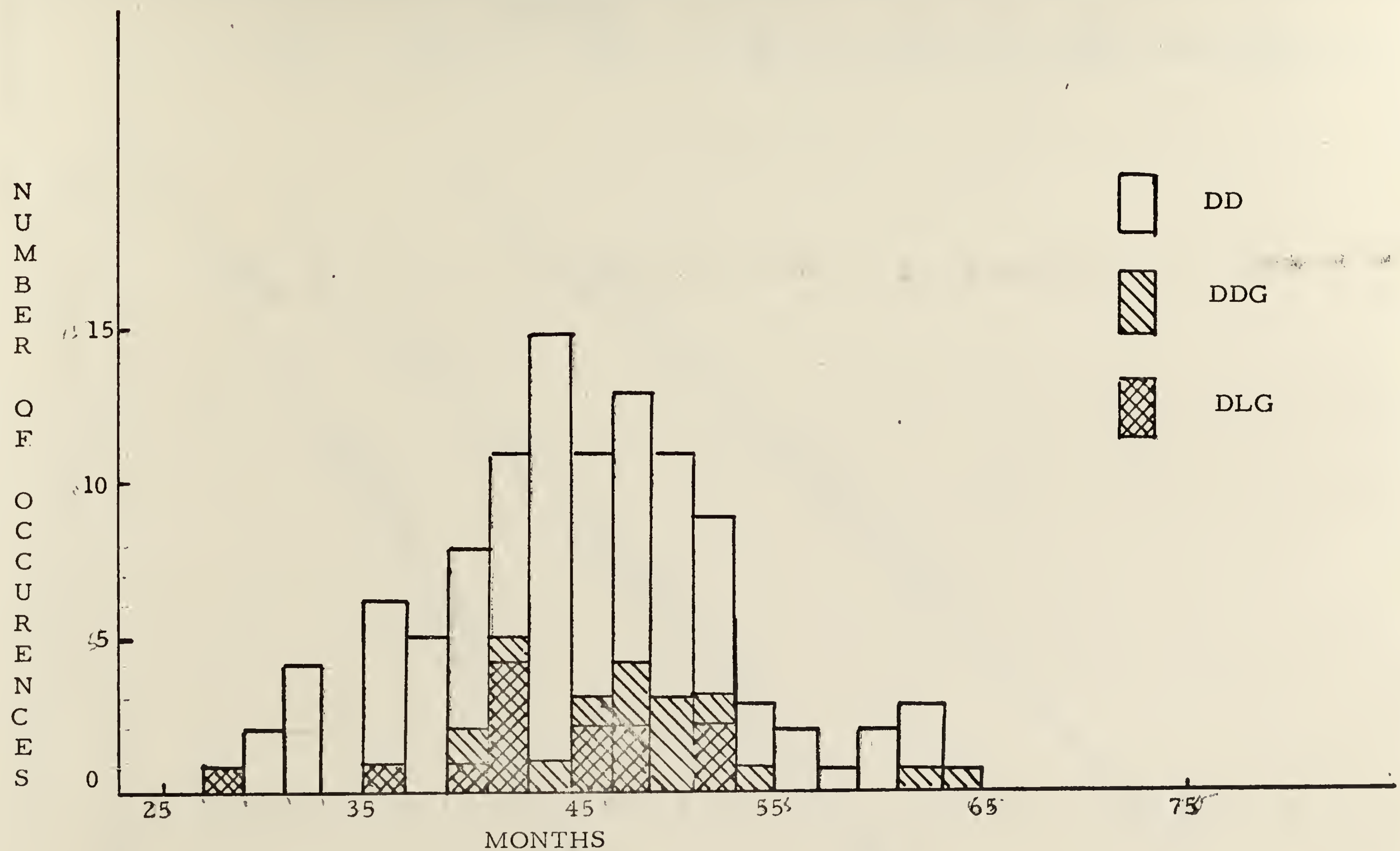
DISTRIBUTION OF MONTHS TO ACCUMULATE 6,000 HOURS AT SEA

FIGURE A-1



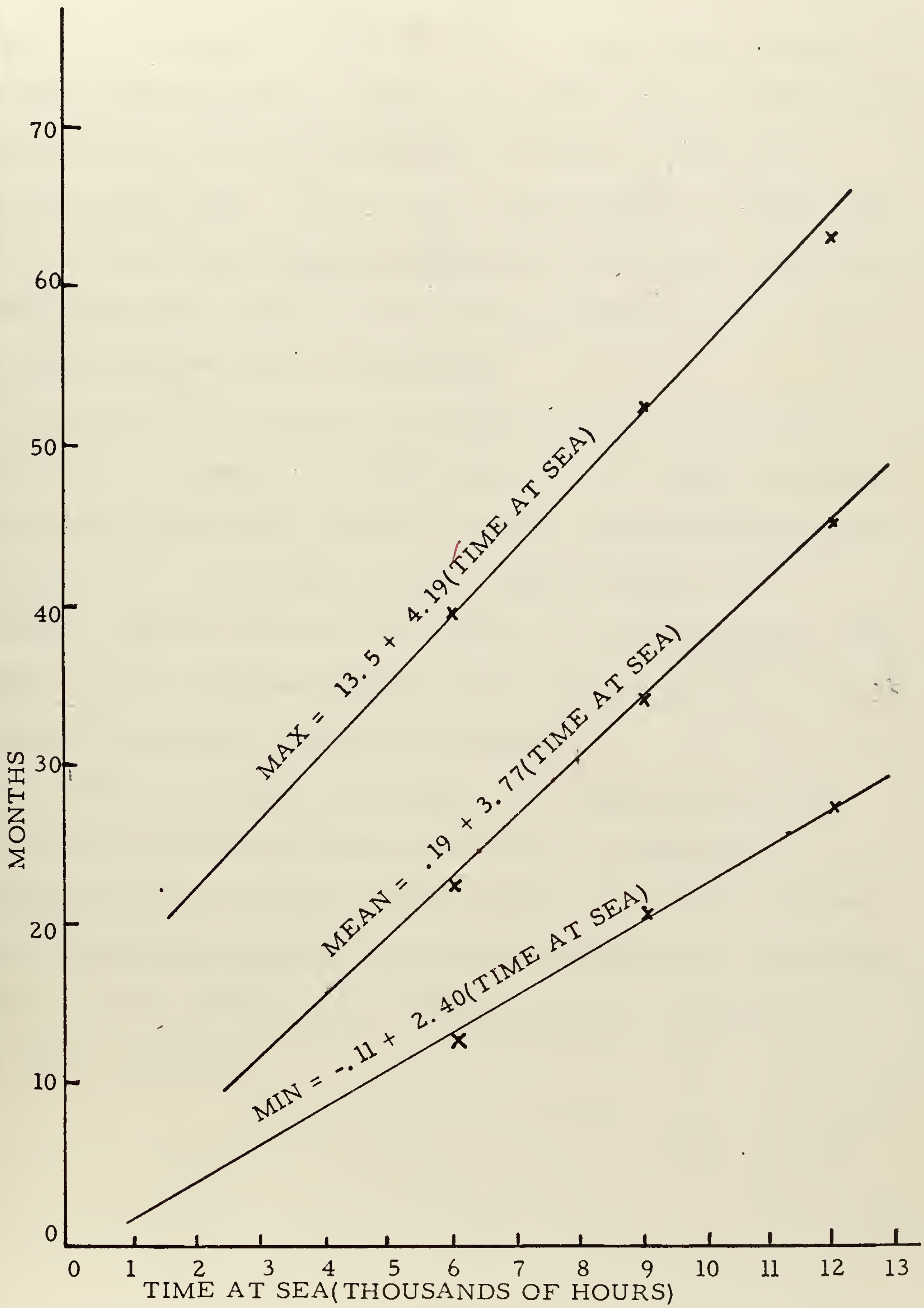
DISTRIBUTION OF MONTHS TO ACCUMULATE 9,000 HOURS AT SEA

FIGURE A-2



DISTRIBUTION OF MONTHS TO ACCUMULATE 12, 000 HOURS AT SEA

FIGURE A-3



REGRESSION OF TIME AT SEA ON CALENDAR MONTHS

FIGURE A-4

maximum, minimum, and mean calendar months are linear functions of the number of hours at sea. It was also assumed that the distribution of months to 12,000 hours at sea was representative of the distribution of time at sea for a destroyer type ship. Time at sea was converted to time per engine using the assumption, supplied by PMS-389, that 96% of all operations will be using two engines and 4% of the time four engines will be operated.

Utilizing the linearity and distribution assumptions noted above, a computer program was written which predicted the maximum and minimum months between engine overhauls and distributed all overhauls between these figures in a smoothed version of the 12,000 hours at sea histogram. The output of this program produced distribution function inputs for use in the GPSS simulation program.

A further assumption was that if DD operations tempo was varied, the distribution of months to accumulate a specified number of hours varied linearily. Thus the same computer routine was able to generate distribution function inputs for the simulation of various levels of destroyer operation and TBO's.

APPENDIX B

COSTING INFORMATION

A computer subroutine was written to estimate the cost of various purchase plans. The cost figures developed in this study cannot be considered solid figures for budgeting purposes, but only relative costs of various purchase plans to assist in evaluating various purchase strategies. The only costs considered in this study are holding and purchase costs. A cost estimate of $800,000 for the initial spare engine delivery was received from PMS-389. To this figure a cost escalation of 5% per year was assumed to determine the cost of an engine in succeeding time frames.

The standard inventory theory premise that holding cost is a percentage of the purchase cost was utilized in this study. This holding cost is considered to contain three components. The first component is the actual cost of storing the engines when they are waiting demand from the fleet, including such factors as administrative costs, possible deterioration of the engines from nonuse, packing and preservation costs, cost of the storage facility, etc. The second component of holding cost is the cost associated with investing funds in engines vice other uses. Funds invested in unused engines are not available to meet any other needs of the Navy. The third component is obsolescence cost. This is the cost of making alterations to engines after purchase due to technological improvements. It is

assumed a new engine would be built with all improvements developed up to its construction time incorporated into it, thus the alterations would be required only for previously built engines. A holding cost equal to 12% of the total purchase price per year, as set by PMS-389, was used for all cost estimates in this study.

Annual costs are computed for each year through fiscal year 1994, i.e. twenty years from the scheduled delivery of the first ship. After computation of the yearly costs, system inventory costs are computed. Total system inventory costs are discounted to 1972 dollars using a discount rate of 7.75% per year to enable better comparisons of various purchase plans.

The cost subroutine can be utilized in two modes. In the first application, it is used as a subroutine to the system simulation. In this mode, the subroutine receives as inputs the number of engines required to achieve a specified confidence of having an engine when one is required by the fleet. This is utilized whenever the simulation is run with an unconstrained number of engines. Whenever the simulation demonstrates a need for more engines, than previously required, the purchase cost of the additional engines is computed based on the year in which it is required. All engines purchased are maintained in the rotable pool for the remainder of the system life, even if the simulation shows that fewer engines would be required at a later period of time.

In the second mode, the subroutine costs predetermined purchase plans over the life cycle of the ship system independent of the actual system requirements. The costing of predetermined purchase plans allows comparison of cost to engine weeks lost when the simulation is run in a constrained pool size mode.

The costing subroutine uses initial engine cost, holding cost rate, and discount rate as variable input parameters. This feature allows future testing to determine the change in relative costs as these values are varied.

APPENDIX C

RELIABILITY CONSIDERATIONS

Since the DD 963 class destroyers have not yet been built, good data on engine reliability is not available. An estimate of the order of magnitude of the engine reliability was obtained from the Maintenance Engineering Analysis [Ref. 3] prepared by Litton Industries, which contains estimates of failure frequencies for various engine components.

Table C-I lists the components which, if they fail, will require an engine to be changed. The failure frequency for each component is the number of failures expected in one year of operation based on 2,500 engine hours/year. In the M.E.A., all engine components were assumed to have an exponential failure distributions, thus the failure frequencies for critical components (Table C-I) could be added. The sum of these frequencies can then be converted to an engine removal rate (removals/hour) as follows:

$$\text{Removal Rate (RR)} = \frac{\text{Failure Frequency}}{2500}$$

The probability of an engine having to be removed in some time interval (T) is:

$$Pr(R) = 1-\exp(-RR \times T)$$

COMPONENT	FAILURE FREQUENCY (Failures/Year)
A. Gas Generator	
1. Compressor front frame	0.0012
2. Compressor rotor	0.0018
3. Compressor stator assembly	0.00457
4. Compressor rear frame	0.0012
5. Main bearings	0.0210
6. Combustor	0.0040
7. High pressure turb. rotor	0.0122
8. High pressure turb. stator	0.0024
9. Turbine mid-frame	0.00469
B. LP (Power) Turbine	
1. LP (power) turbine rotor assembly	0.0024
2. LP (power) turbine stator assembly	0.0037
3. LP (power) turbine rear frame	0.0012

FAILURE FREQUENCIES FOR CRITICAL COMPONENTS

TABLE C-I

It was desired to know the probablity of an engine having to be removed prior to its scheduled overhaul time, therefore (T) in the above equation was taken as TBO. These probabilities are tabulated in Table C-II for various TBO's.

EARLY FAILURE PROBABILITIES

TBO	Pr(R)
4,000	.092
6,000	.135
8,000	.176
10,000	.215
12,000	.252

TABLE C-II

Instead of assuming that the given failure frequencies were true and then using the Pr(R) corresponding to each TBO, the value for 6,000 hr (.135) was used in the base case and the simulation was tested for sensitivity to changes in this value. This implies that as TBO increases, failure frequency decreases in the simulation.

APPENDIX D

NORMALITY OF RUNS

The simulation was run ten times for each choice of variables and the number of spare engines required at each point in time was tabulated after each run. The GPSS program calculated the mean and standard deviation of number of engines at each point in time. In order to determine confidence limits on these results, it was necessary to assume some distribution. Since the data appeared to be normal, a Kolmogorov-Smirnov test against the Normal Distribution was made for several large samples. The null hypothesis that the number of engines required at various points in time is normally distributed could not be rejected for a significance level of 0.05 in any case. For samples taken beyond 100 weeks of system life, the null hypothesis could not be rejected for significance levels as high as 0.6.

APPENDIX E

DETAILED MODEL DESCRIPTION

A. CONTROL INFORMATION

The primary variables which may be altered in order to establish the nature of the simulation model are:

NRUNS	Number of observations/interval. Number of START/CLEAR cards.
NTIME	Number of time intervals of interest.
INCRE	Interval between time-slices.
START	Delay in starting statistical accumulation.
RAND	Percentage of random failures.
TRANS	Transportation delay, includes shipping ship to ship.
NPOOL	Number of engines loaded initially.
OPER	Holds function number which sets TBO growth or replacement time dist. to be considered.
LEARN	Function which established rework facility learning curve.
LOT	Number below which the number of engines undergoing rework must fall to allow an engine to be induced early. OPTION 3
PFLAG	Delay of the PF program over launching of DD 963. OPTION 2
LOADj	Number of engines to be loaded in the jth load. OPTION 4
TIMEj	Time delay prior to loadj. OPTION 4
DPLOY	Percentage of ships on deployment whose engines must be extended. OPTION 3
PCNTM	1/PCNTM=Percentage of TBO which an engine may be extended. OPTION 3
FAC STORAGE JJ	Capacity of rework facility is JJ.

JJ FUNCTION	Function JJ contains replacement time for TBO and operating schedule. (Held in SAVEVALUE OPER)
SHIPS	Function which determines delivery schedule schedule of DD's.
DIFF	Variable which measures number of engines in pipeline.
RMULT	Contains the seed of the random number generators used.
J FUNCTION	Contains the TBO growth rate to be used.

The basic time step for this model is one week. This implies that all operations transpire in units of integer weeks. If finer detail is needed the basic time step may be altered by changing seven-ten cards in the main deck.

B. ACCUMULATION OF STATISTICS

Statistics are accumulated for NTIME(120) periods each run for NRUNS(10) runs. Interval between "looks" is INCRE(8) weeks. General logic flow is contained in the flow charts.

C. INDIVIDUAL BLOCK DESCRIPTIONS

Detailed explanations of the individual GPSS instructions are contained in the GPSS User's Manual [Ref. 2].

D. SUPPORTING FORTRAN SUBROUTINES

General logic flow for the fortran subroutines is contained in Appendix G.

APPENDIX F

ACCURACY OF THE MODEL

During preliminary runs, much use was made of the TRACE and PRINT block options of GPSS. These blocks enable the analyst to chart carefully the transaction's progress through the model, as well as observing the values of key savevalues and parameters. Extensive use was made of the current events chain to verify proper information storage. Examination of the information thus proviced indicated that the model was performing as intended.

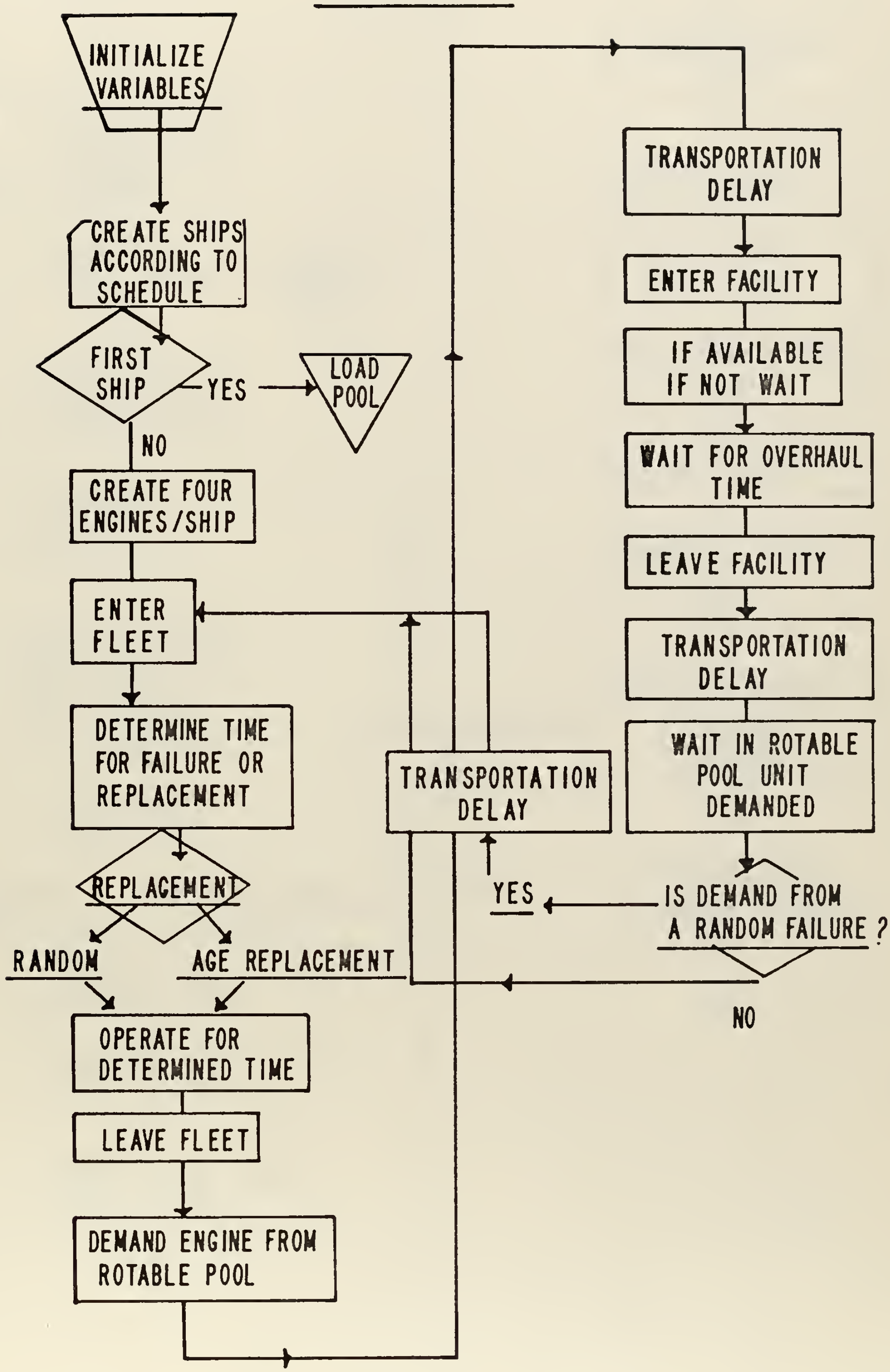
In an effort to establish the basic correctness of the model, a completely deterministic system was simulated by hand. The results of this nonstochastic hand simulation were compared to the model results with all stochastic elements removed. The results compared very favorably.

APPENDIX G

MODEL FLOW CHART

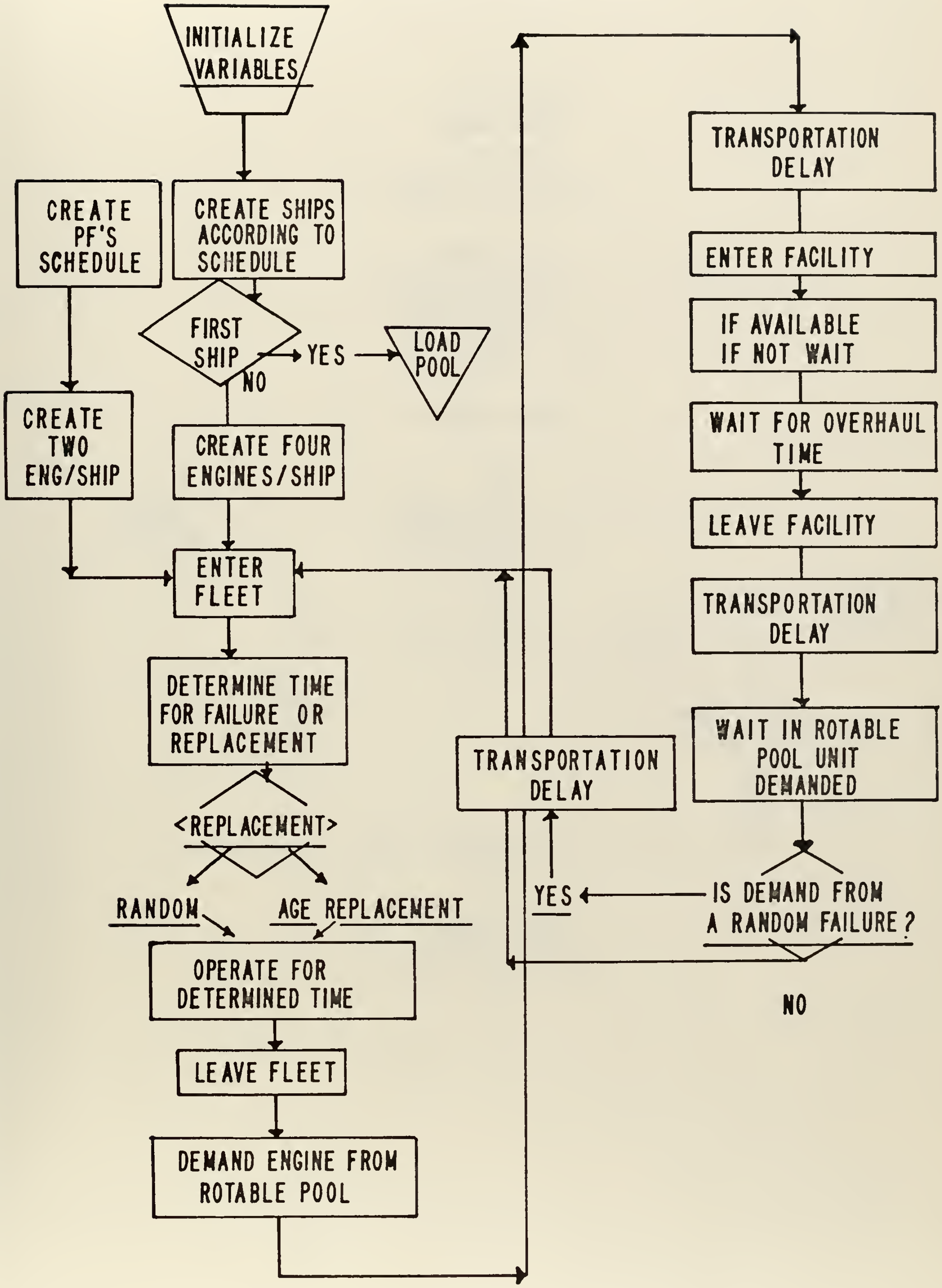
OPTION I

BASE CASE

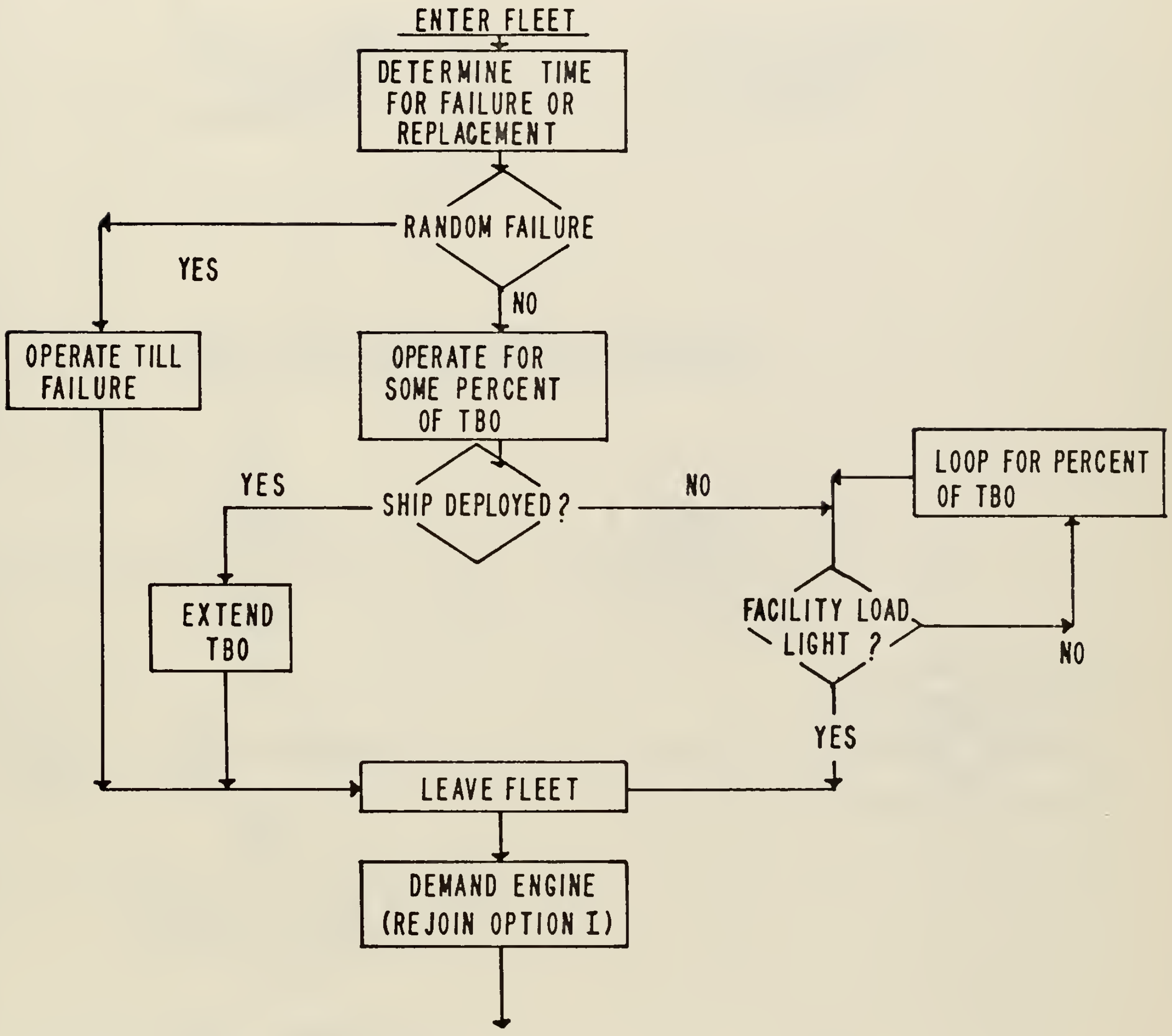


OPTION II

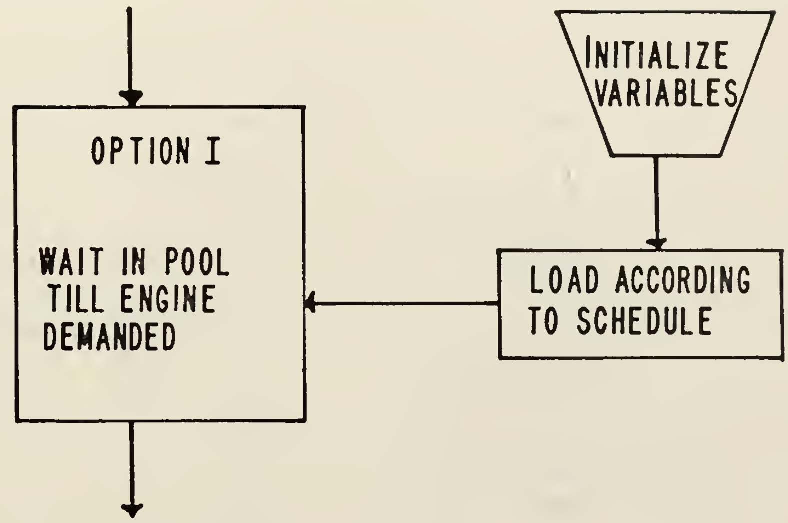
BASE CASE WITH PF'S



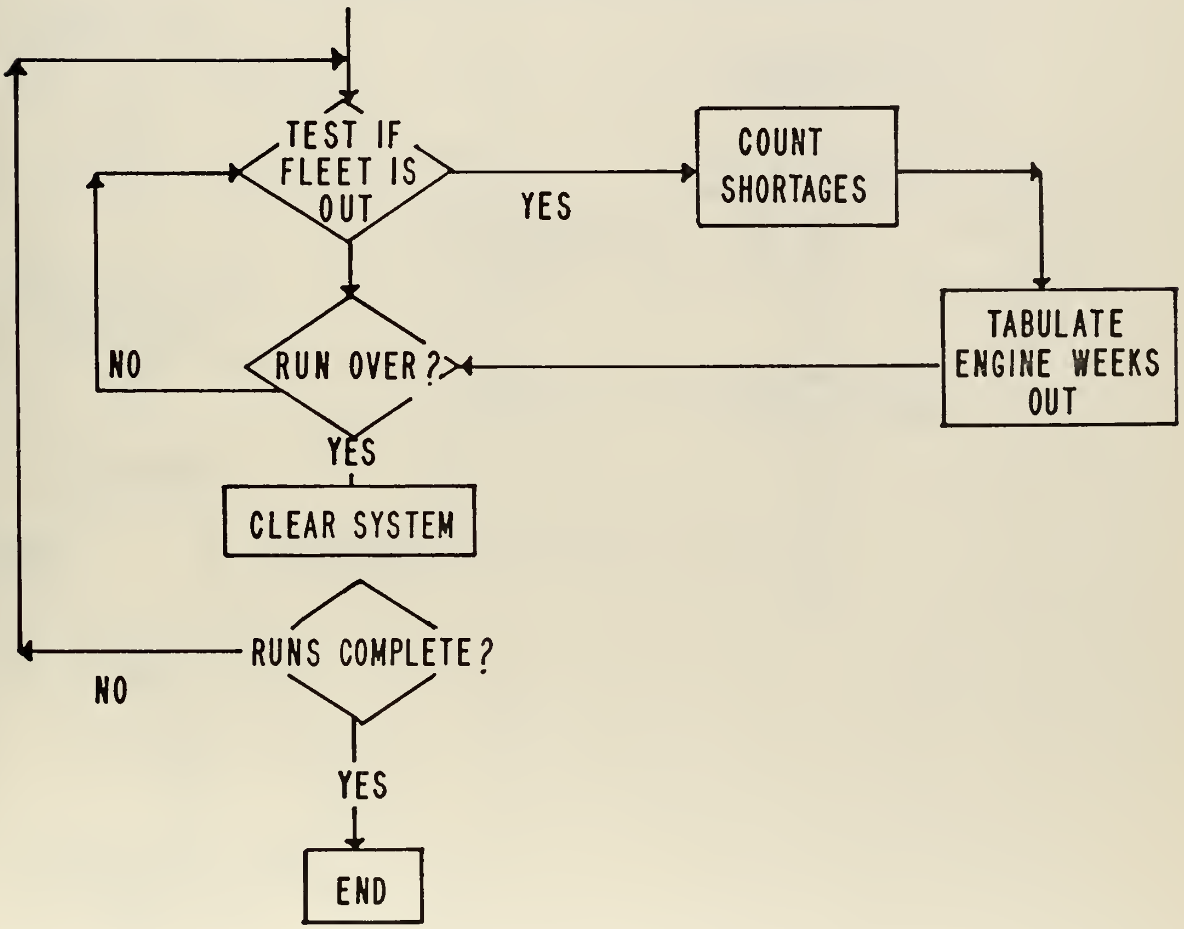
OPTION III
MANAGEMENT
OPTIONS
SAME AS OPTION I



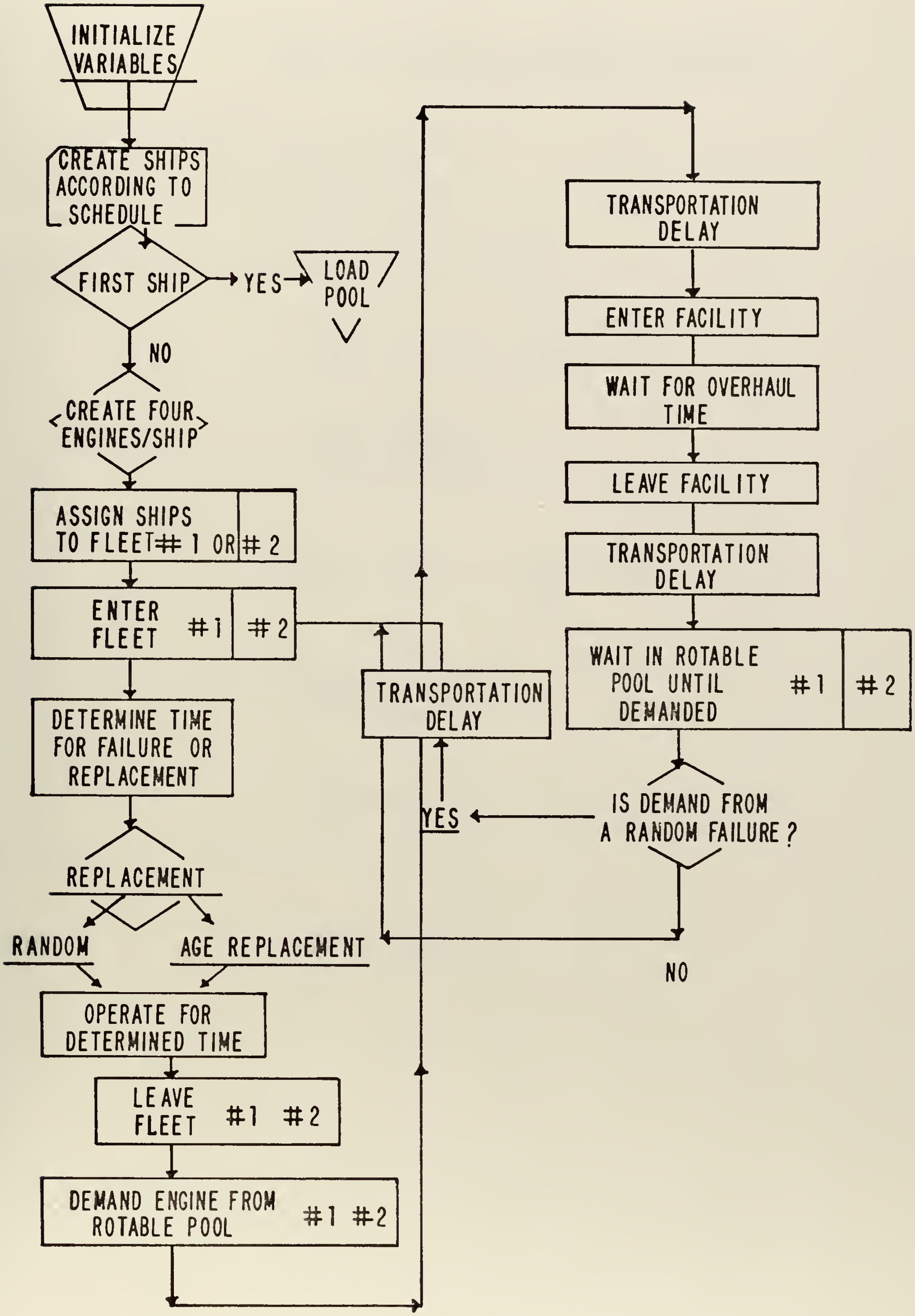
OPTION IV
TESTING OF PURCHASE PLANS



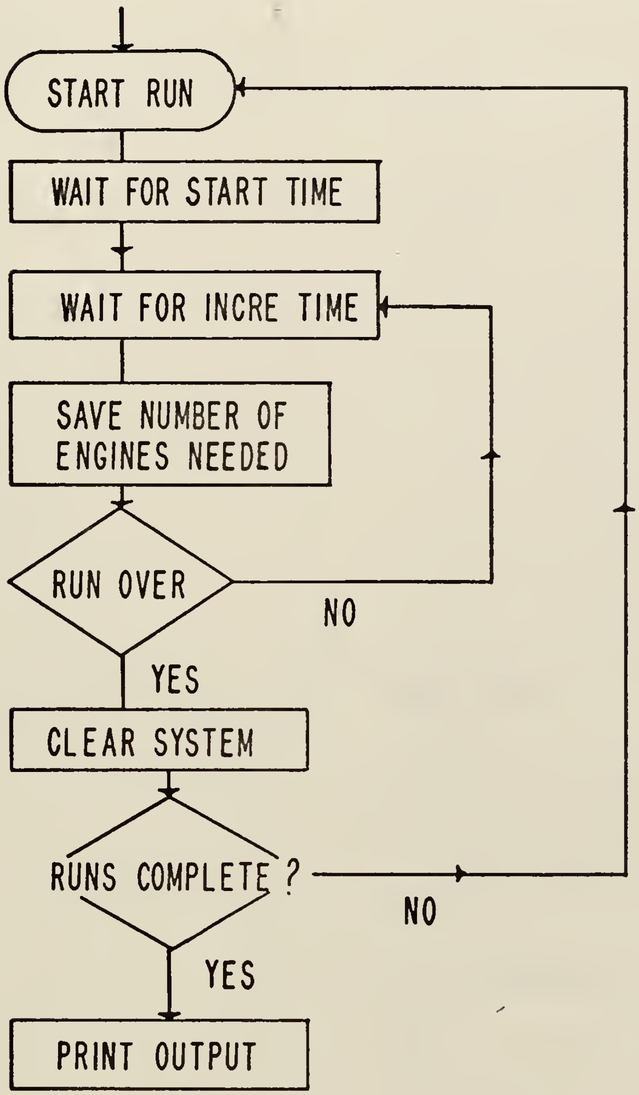
STATISTICS SECTION FOR OPTION IV



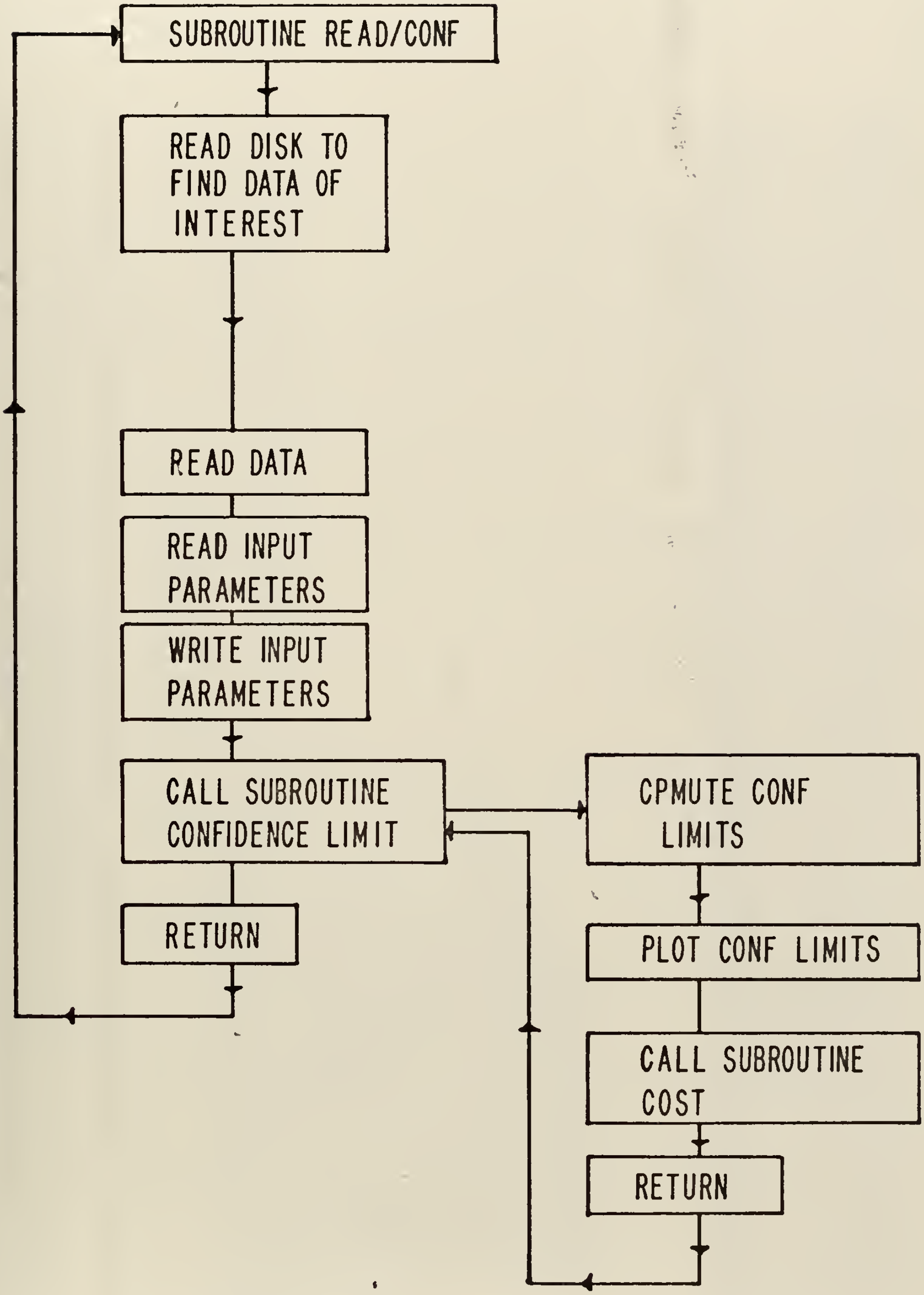
OPTION V
SPLIT ROTABLE POOL



GPSS STATISTICS SECTION (GENERAL)



SUPPORTING ROUTINES



```
****************************************************************

                    COMPUTER PROGRAMS

****************************************************************


//GOATS122  JOB (0622,0562FT,ROLO),'GAUTIER',TIME=4
//JOBLIB DD DSNAME=GPSS,DISP=SHR
// EXEC GPSS,REGION.GO=150K,TIME.GO=5
//GO.DOUTPUT DD UNIT=SYSDA,SPACE=(CYL,6),DCB=BLKSIZE=3591,DSN=&TEMP,
//   DISP=(NEW,PASS)
//GO.DINTERO DD SPACE=(CYL,2)
//GO.DSYMTAB DD SPACE=(CYL,2)
//GO.DREPTGEN DD SPACE=(CYL,2)
//GO.DINTWORK DD SPACE=(CYL,2)
//GO.SYSIN DD *
      REALLOCATE COM,40000
      REALLOCATE QUE,010,BLO,100,LOG,010
      REALLOCATE FSV,2500,FAC,000
      REALLOCATE CHA,0,BVR,0
      REALLOCATE STO,005,VAR,020
      REALLOCATE FMS,0,HMS,0
      REALLOCATE XAC,300
      REALLOCATE TAB,121


****************************************************************
****************************************************************

BASE CASE.  THIS PROGRAM SIMULATES THE OPERATION OF THE ENGINE INVENTORY
SYSTEM WITH THOSE ENGINES EXPECTED FORM A FLEET OF 30 963 CLASS SHIPS

****************************************************************
****************************************************************

      SIMULATE
*
      RMULT      1,7                    SET THE SEEDS OF THE RANDOM
*                                       NUMBER GENERATORS USED
*
*     INITIAL INPUTS ARE AS FOLLOWS
*
```

```
       NRUNS== NO. OF OBSERVATIONS/TIME SLICE
       NTIME==NO. OF TIME SLICES TO BE OBSERVED
       INCRE==INTERVAL OF TIME BETWEEN TIME SLICES
       START==DELAY BEFORE STARTING STATISTICAL ACCUMULATION
       RAND==PERCENTAGE OF RANDOM FAILURES
       TRANS==SYSTEM TRANSIT DELAY
       NPOOL==NUMBER OF ENGINES PRELOADED INTO THE ROTABLE POOL
       INT==ARGUMENT FOR FUNCTION SHIPS ( NOT TO BE CHANGED )
*
*
*
*
        INITIAL     XH$NRUNS,K10
        INITIAL     XH$NTIME,K120
        INITIAL     XH$INCRE,K8
        INITIAL     XH$START,K1
        INITIAL     XH$RAND,K135
        INITIAL     XH$TRANS,K3
        INITIAL     XH$INT,K1
        INITIAL     XH$NPOOL,K100
*
*
*
*
 SHIPS FUNCTION    XH$INT,L30
     1      0     2     24     3     8     4     4     5    12     6    16
     7      8     8      8     9     4    10     8    11     4    12     4
    13      4    14      4    15     4    16     4    17     4    18     4
    19      8    20      4    21     4    22     4    23     4    24     4
    25      4    26      4    27     4    28     4    29     4    30     4
*
*
*
 LEARN FUNCTION    N$LEARN,D5          LEARNING CURVE (REWORK FACILITY)
0,7/10,6/20,5/30,4/30000,4
*
*      FUNCTIONS TO INCREASE TBO WITH TIME
*
    1 FUNCTION    C1,E4
0,FN26/156,FN27/208,FN28/260,FN34
  2 FUNCTION    C1,E4
0,FN26/208,FN27/260,FN28/312,FN34
    3 FUNCTION    C1,E4
0,FN26/260,FN27/312,FN28/364,FN34
    4 FUNCTION    C1,E4
0,FN26/312,FN27/364,FN28/416,FN34
    5 FUNCTION    C1,E6
0,FN26/208,FN27/260,FN28/312,FN34/416,FN12/520,FN24
```

```
*
*
*     FUNCTIONS TO DETERMINE REPLACEMENT TIME AS A FUNCTION OF
*     TIME BETWEEN OVERHAUL (TBO) AND OPERATING SCHEDULE
*
*
 11     FUNCTION   RN2,C19
.009,110./.028,118./.047,126./.074,133./.120,141./.175,149./
.249,157./.342,165./.462,172./.582,180./.702,188./.804,196./
.878,204./.915,212./.944,219./.963,227./.982,235./.991,243./
1.000,251.
 12     FUNCTION   RN2,C19
.009,165./.028,175./.047,185./.074,195./.120,205./.175,215./
.249,226./.342,236./.462,246./.582,256./.702,266./.804,276./
.878,286./.915,296./.944,306./.963,316./.982,326./.991,336./
1.000,347.
 13     FUNCTION   RN2,C19
.009,220./.028,232./.047,245./.074,257./.120,269./.175,282./
.249,294./.342,307./.462,319./.582,331./.702,344./.804,356./
.878,368./.915,381./.944,393./.963,405./.982,418./.991,430./
1.000,443.
 14     FUNCTION   RN2,C19
.009,275./.028,290./.047,304./.074,319./.120,334./.175,348./
.249,363./.342,378./.462,392./.582,407./.702,421./.804,436./
.878,451./.915,465./.944,480./.963,495./.982,509./.991,524./
1.000,539.
 15     FUNCTION   RN2,C19
.009,330./.028,347./.047,364./.074,381./.120,398./.175,415./
.249,432./.342,448./.462,465./.582,482./.702,499./.804,516./
.878,533./.915,550./.944,567./.963,584./.982,601./.991,618./
1.000,635.
 16     FUNCTION   RN2,C19
.009,094./.028,101./.047,109./.074,116./.120,123./.175,130./
.249,137./.342,144./.462,151./.582,159./.702,166./.804,173./
.878,180./.915,187./.944,194./.963,201./.982,209./.991,216./
1.000,223.
 17     FUNCTION   RN2,C19
.009,141./.028,151./.047,160./.074,169./.120,178./.175,187./
.249,196./.342,205./.462,214./.582,223./.702,232./.804,242./
.878,251./.915,260./.944,269./.963,278./.982,287./.991,296./
1.000,305.
 18     FUNCTION   RN2,C19
.009,189./.028,200./.047,211./.074,222./.120,233./.175,244./
.249,255./.342,266./.462,277./.582,288./.702,299./.804,310./
.878,321./.915,332./.944,344./.963,355./.982,366./.991,377./
1.000,388.
 19     FUNCTION   RN2,C19
.009,236./.028,249./.047,262./.074,275./.120,288./.175,301./
```

```
.249,314./.342,327./.462,340./.582,353./.702,366./.804,379./
.878,392./.915,405./.944,418./.963,431./.982,444./.991,457./
1.000,470.
 20     FUNCTION    RN2,C19
.009,283./.028,298./.047,313./.074,328./.120,343./.175,358./
.249,373./.342,388./.462,403./.582,418./.702,432./.804,447./
.878,462./.915,477./.944,492./.963,507./.982,522./.991,537./
1.000,552.
 21     FUNCTION    RN2,C19
.009,080./.028,087./.047,093./.074,100./.120,106./.175,113./
.249,119./.342,126./.462,133./.582,139./.702,146./.804,152./
.878,159./.915,165./.944,172./.963,178./.982,185./.991,192./
1.000,198.
 22     FUNCTION    RN2,C19
.009,120./.028,128./.047,136./.074,145./.120,153./.175,161./
.249,169./.342,178./.462,186./.582,194./.702,202./.804,210./
.878,219./.915,227./.944,235./.963,243./.982,252./.991,260./
1.000,268.
 23     FUNCTION    RN2,C19
.009,160./.028,170./.047,180./.074,190./.120,200./.175,209./
.249,219./.342,229./.462,239./.582,249./.702,259./.804,269./
.878,279./.915,288./.944,298./.963,308./.982,318./.991,328./
1.000,338.
 24     FUNCTION    RN2,C19
.009,200./.028,212./.047,223./.074,235./.120,246./.175,258./
.249,269./.342,281./.462,292./.582,304./.702,315./.804,327./
.878,338./.915,350./.944,362./.963,373./.982,385./.991,396./
1.000,408.
 25     FUNCTION    RN2,C19
.009,240./.028,253./.047,266./.074,280./.120,293./.175,306./
.249,319./.342,332./.462,346./.582,359./.702,372./.804,385./
.878,398./.915,412./.944,425./.963,438./.982,451./.991,464./
1.000,477.
 26     FUNCTION    RN2,C19
.009,066./.028,072./.047,078./.074,084./.120,090./.175,096./
.249,102./.342,108./.462,114./.582,120./.702,126./.804,132./
.878,138./.915,144./.944,150./.963,156./.982,162./.991,168./
1.000,174.
 27     FUNCTION    RN2,C19
.009,098./.028,105./.047,113./.074,120./.120,127./.175,135./
.249,142./.342,149./.462,156./.582,164./.702,171./.804,178./
.878,186./.915,193./.944,200./.963,208./.982,215./.991,222./
1.000,230.
 28     FUNCTION    RN2,C19
.009,132./.028,141./.047,149./.074,158./.120,167./.175,176./
.249,184./.342,193./.462,202./.582,210./.702,219./.804,228./
.878,237./.915,245./.944,254./.963,263./.982,272./.991,280./
1.000,289.
```

```
 29     FUNCTION   RN2,C19
.009,053./.028,058./.047,064./.074,069./.120,075./.175,080./
.249,085./.342,091./.462,096./.582,102./.702,107./.804,113./
.878,118./.915,123./.944,129./.963,134./.982,140./.991,145./
1.000,151.
 30     FUNCTION   RN2,C19
.009,106./.028,113./.047,121./.074,128./.120,136./.175,144./
.249,151./.342,159./.462,167./.582,174./.702,182./.804,189./
.878,197./.915,205./.944,212./.963,220./.982,228./.991,235./
1.000,243.
 31     FUNCTION   RN2,C19
0.009,247./.028,260./.047,274./.074,287./.120,300./.175,314./
0.249,327./.342,341./.462,354./.582,368./.702,381./.804,395./
0.878,408./.915,422./.944,435./.963,449./.982,462./.991,476./
1.000,489.
 32     FUNCTION   RN2,C19
0.009,211./.028,223./.047,235./.074,247./.120,259./.175,270./
0.249,282./.342,294./.462,306./.582,318./.702,330./.804,342./
0.878,354./.915,366./.944,378./.963,390./.982,402./.991,414./
1.000,426.
 33     FUNCTION   RN2,C19
0.009,180./.028,191./.047,201./.074,212./.120,223./.175,234./
0.249,244./.342,255./.462,266./.582,276./.702,287./.804,298./
0.878,308./.915,319./.944,330./.963,341./.982,351./.991,362./
1.000,373.
 34     FUNCTION   RN2,C19
0.009,148./.028,157./.047,166./.074,176./.120,185./.175,194./
0.249,204./.342,213./.462,223./.582,232./.702,241./.804,251./
0.878,260./.915,269./.944,279./.963,288./.982,297./.991,307./
1.000,316.
 35     FUNCTION   RN2,C19
0.009,119./.028,127./.047,135./.074,143./.120,151./.175,160./
0.249,168./.342,176./.462,184./.582,192./.702,201./.804,209./
0.878,217./.915,225./.944,233./.963,241./.982,250./.991,258./
1.000,266.
```

```
*
*
*       GENERATE SHIPS ACCORDING TO SCHEDULE
*
*
*
        GENERATE    FN$SHIPS,,,30
        SAVEVALUE   INT+,K1,H
*
*      THIS SECTION INITIALIZES THE POOL TO NPOOL WITH THE FIRST SHIP
*
*
FIRST   MARK
        TEST E      N$FIRST,K1,HOP
        SPLIT       XH$NPOOL,STOCK
  HOP   MARK
*
*
        SPLIT       3,NEXT
 NEXT   MARK
*
*
FLEET   ENTER       NAV
*
        SAVEVALUE   OPER,FN24,H                DETERMINE REPLACEMENT TIME HERE
*
        TRANSFER    .XH$RAND,RNAV,RFAIL        RANDOM FAILURES SPLIT HERE
 RNAV   ADVANCE     XH$OPER
 JOIN   LEAVE       NAV
        LOGIC S     1                          DEMAND ENGINE FROM FLEET
*
        ADVANCE     XH$TRANS,1                 TRANSPORT DELAY
*
        QUEUE       FAC                        ARRIVE AT REWORK FACILITY
        ENTER       FAC
        DEPART      FAC
        ADVANCE     FN$LEARN,1                 REWORK TIME WITH LEARNING CURVE
LEARN   LEAVE       FAC
*
STOCK   QUEUE       POOL                       ENGINES NOW READY FOR ISSUE
*
        ADVANCE     XH$TRANS,1                 TRANSPORT DELAY
*
        GATE LS     1                          HOLD ENGINES UNTIL DEMANDED
*
        DEPART      POOL
        LOGIC R     1
 XXX4   TEST NE     XH$TALLY,K1,RDLAY          IS THE FAILURE A RANDOM ONE?
```

```
       TRANSFER   ,FLEET                  SEND NEW ENGINE TO THE FLEET
*
*     RFAIL PACKAGE FOR RANDOM FAILURES
*
RFAIL MARK
*
       ADVANCE    V$MEAN,V$MEAN           FAIL UNIFORMLY ON THE INTERVAL
*                                         FROM REPLACEMENT TO TBO
*
       SAVEVALUE  TALLY,K1,H              MARK THE RANDOM FAILURES
       TRANSFER   ,JOIN
*
*     RANDOMLY FAILED ENGINES ARE DELAYED ENR FLEET HERE
*
RDLAY MARK
       SAVEVALUE  TALLY,KO,H
       ADVANCE    XH$TRANS,1              TRANSPORT DELAY
       TRANSFER   ,FLEET
*
*
************************************************************************
************************************************************************

THIS SECTION ACCUMULATES THE STATISTICS FROM THE GPSS MODEL THAT
ARE SENT TO THE FORTRAN SUBROUTINES FOR PROCESSING.

************************************************************************
************************************************************************
*
*
*     THIS LOOP STORES Q LENGTHS IN SAVEVALUES
*
       GENERATE   ,,,1
*
*
       ADVANCE    XH$START                INITIAL PROGRAM DELAY
       ASSIGN     7,XH$NTIME              EVALUATE THE SYSTEM NTIMES
  TRIP ADVANCE    XH$INCRE                INTERVAL BETWEEN "LOOKS"
       SAVEVALUE  ONE+,1,H
       ASSIGN     8,XH$ONE
       SAVEVALUE  *8,V$DIFF
       LOOP       7,TRIP
*
       SAVEVALUE  TWO+,1,H
*
       TEST E     XH$TWO,XH$NRUNS,KILL
*
*     TABULATING LOOP
```

```
*
        ASSIGN      5,V$DATA
        ASSIGN      1,1
        ASSIGN      2,1
  XXX   ASSIGN      3,X*1
        TABULATE    *2                        TABULATE VARIABLE OF INTEREST
        ASSIGN      1+,1
        ASSIGN      2+,1
        TEST E      P2,V$ADD,ONW
        ASSIGN      2,1
  ONW   LOOP        5,XXX
*
*
*
  KILL  MARK
        SAVEVALUE   INT,K1,H
        TERMINATE   1
*
*
*
  DIFF  VARIABLE    XH$NPOOL-Q$POOL           NO. OF ENGINES IN PIPELINE
   ADD  VARIABLE    XH$NTIME+K1
  DATA  VARIABLE    XH$NTIME*XH$NRUNS         NO. OF DATA POINTS TO BE SAVED
 SMART  FVARIABLE   XH$OPER*9/10
  MEAN  VARIABLE    XH$OPER/2
   FAC  STORAGE     4                         CAPACITY OF THE REWORK FACILITY
*
   NAV  STORAGE     120                       CAPACITY OF THE FLEET
*
*
*
*
*
**********************************************************************
*
*     121 TABLES OF THE FOLLOWING FORM ARE CONTAINED HERE
*
     1 TABLE        *3,0,1,40
*
**********************************************************************
*
*
*
*
*
*
*     RETAIN SAVEVALUES OF INTEREST
*
```

```
1 START         1
  CLEAR         X1-X2500,XH1-XH20
1 START         1,NP
  CLEAR         X1-X2500,XH1-XH20
1 START         1,NP
  CLEAR         X1-X2500,XH1-XH20
1 START         1,NP
  CLEAR         X1-X2500,XH1-XH20
1 START         1,NP
  CLEAR         X1-X2500,XH1-XH20
1 START         1,NP
  CLEAR         X1-X2500,XH1-XH20
1 START         1,NP
  CLEAR         X1-X2500,XH1-XH20
1 START         1,NP
  CLEAR         X1-X2500,XH1-XH20
1 START         1,NP
  CLEAR         X1-X2500,XH1-XH20
1 START         1
*
*      RUNS = TEN
*
        REPORT                          PRINT STATISTICS OF INTEREST
        FORMAT      1-1/T1,T3,T4
 2      FORMAT      1-120/T1,T3,T4
 9      FORMAT      1-20/XH1,XH2        WPITE OUT SAVEVALUES
        END


************************************************************************
************************************************************************

THIS SECTION READS GPSS DATA FROM THE DISK

************************************************************************
************************************************************************


// EXEC FORTCLGP,COND.LINK=EVEN,COND.GO=EVEN,REGION.GO=150K
//FORT.SYSIN DD *
      DIMENSION A(300), B(300), C(300)
      DIMENSION D(900,4),E(900)
      CATA NONE /' 1  '/
      CO 111 I=1,300
      A(I)=0.0
```

```
      B(I)=0.0
      C(I)=0.0
  111 CONTINUE
C
      CALL READ (NTIME, A, B, C )
C   CALLING ARGUMENTS ARE NO. OF TIME SLICES OF INTEREST==NTIME
C   TABLE NO.==A    MEAN==B     STD.DEV.==C
C
      CALL READ (120  , A , B, C )
      STOP
      END




      SUBROUTINE READ ( N , A , B , C )
      DIMENSION A(N)  , B(N), C(N)
      DIMENSION D(900 ,4) , E(900)
      DATA NONE /' 1  '/
      CALL REREAD
 50   READ (4,100,END=600) JJ
 100  FORMAT (2X,A2)
      IF (JJ.EQ.NONE) GO TO 200
      GO TO 50
 200  CONTINUE
      READ (99,20) A(1), B(1), C(1)
   20 FORMAT (1X,F5.0,2F21.3)
      DO 999 K=1,75
      READ (4,20,END=600) A(K), B(K), C(K)
      WRITE (6,20)        A(K), B(K), C(K)
  999 CONTINUE
C
C     REMOVE EFFECTS OF GPSS PAGE SKIP
C
      READ (4,20,END=600) XX1,XX2,XX3
C
      DO 998 K=76,N
      READ (4,20,END=600) A(K), B(K), C(K)
      WRITE (6,20)        A(K), B(K), C(K)
  998 CONTINUE
C
C     NOW READ INPUT PARAMETERS
C
      READ (4,21,END=600) XNRUN
      READ (4,21,END=600) XNTIM
      READ (4,21,END=600) XINC
      READ (4,21,END=600) START
```

```
      READ (4,21,END=600) RAND
      READ (4,21,END=600) TRANS
C
C     WRITE INPUT PARAMETERS
C
      WRITE (6,21) XNTIM, XNRUN, XINC, START
      WRITE (6,21) RAND, TRANS
   21 FORMAT (14X,4F10.3)
      NTIME=XNTIM
  600 WRITE(6,700)
  700 FORMAT(' END-OF-FILE.')
      CALL CLIM(NTIME,XNRUN,A,B,C,D,E,XINC,START)
      RETURN
      END
C


****************************************************************************
****************************************************************************

THIS SECTION COMPUTES CONFIDENCE LIMITS FOR THE NO. OF ENGINES REQUIRED

****************************************************************************
****************************************************************************


C

      SUBROUTINE CLIM IS CALLED AUTOMATICALLY WITH VALUES COMPUTED ABOVE
C

      SUBROUTINE CLIM (NTIME,RUNS,WK,X,S,C,CL,TINC,SP)
      DIMENSION X(NTIME),S(NTIME),CL(NTIME),WK(NTIME),C(NTIME,4),Z(4)
      REAL LAB(4)
      REAL LABLE /'     '/
      REAL*8 TITLE(12)
      DATA LAB(1)/'75%'/,LAB(2)/'85%'/,LAB(3)/'95%'/,LAB(4)/'99%'/,Z(1)
     C/0.67/,Z(2)/1.04/,Z(3)/1.645/,Z(4)/2.333/
    9 FORMAT(6A8)
   13 FORMAT('1',' TIME(WK)',31X,'NUMBER OF ENGINES REQUIRED')
   14 FORMAT(' ',12X,'AVERAGE',4X,'75% CONF.LEVEL',4X,'85% CONF.LEVEL',
     C4X,'95% CONF.LEVEL',4X,'99% CONF.LEVEL',///)
   15 FORMAT(' ',2X,F6.0,5X,F7.3,6X,F7.3,13X,F7.3,13X,F7.3,13X,F7.3)
C
C  CALCULATE U.C.L.S FOR EACH TIME PERIOD
```

```
C
      DO 6 J=1,4
      DO 5  I=1,NTIME
    5 C(I,J)=X(I)+Z(J)*S(I)/SQRT (RUNS)
    6 CONTINUE
      DO 12 I=1,NTIME
   12 WK(I)=-SP-WK(I)*TINC
C PLOT RESULTS
      READ (5,9) TITLE
      DO 8 J=1,4
      IF (J.EQ.1)N=1
      IF(J.GT.1)N=2
      IF(J.GT.3)N=3
      LABLE=LAB(J)
      DO 7 I=1,NTIME
    7 CL(I)=C(I,J)
C
C     IN-HOUSE ROUTINE TO PLOT RESULTS OF CONF. LIMITS
C
      CALL DRAW(NTIME,CL,WK,N,0,LABLE,TITLE,5.,0,15,0,1,2,9,15,1,LAST)
C
    8 CONTINUE
      WRITE (6,13)
      WRITE (6,14)
      WRITE (6,15)(WK(I),X(I),C(I,1),C(I,2),C(I,3),C(I,4),I=1,NTIME)
      CALL COST(C,.12,NTIME,.0775,0.8,TINC,SP)
      RETURN
      END
C

************************************************************************
************************************************************************


SUBROUTINE COST COMPUTES THE NUMBER OF ENGINES THAT SHOULD BE PURCHASED
AS A FUNCTION OF CONFIDENCE LEVEL FROM THE DATA FURNISHED BY THE GPSS
PROGRAM.  IT THEN COSTS OUT THIS BUY TO YIELD THE TWENTY YEAR LIFE COSTS

************************************************************************
************************************************************************
```

```
      SUBROUTINE COST(POOL,CHR,N,A,UCI,TI,ST)
      DIMENSION POOL(N,4),AURCST(4),APRCST(4),AHCST(4),ADHCST(4)
      DIMENSION TYPC(20),TYHC(20),UNITS(20)
C
C  CALLING ARGUMENTS ARE POOL--ARRAY OF MEANS,  CHR--HOLDING COST RATE
C  N--NUMBER OF MEANS IN POOL, A--DISCOUNT RATE,  UCI--HOLDING COST RATE
C  TI--LENGTH OF TIME INCREMENTS(WEEKS),  ST-- START TIME
C
C
      WRITE(6,1111)
 1111 FORMAT('1',T40,'ALL COSTS IN MILLIONS OF DOLLARS')
C
C  DETERMINE CALENDER START TIME
C
      STIM=2.0
      STA=ST
    2 STA=STA-52
      IF(STA.LT.0.0) GO TO 4
      STIM=STIM+1.
      UCI=UCI*1.05
      IF(STA.LT.52.) GO TO 5
      GO TO 2
    4 STA=ST
    5 RA=(A*TI)/52.
      DO 900 J=1,4
      UC=UCI
      TIME=STA
      UNTS=0.0
      YHC=0.0
      YPC=0.0
C
C  SET CONFIDENCE LEVEL
C
      IF(J.EQ.1) ICL=75
      IF(J.EQ.2) ICL=85
      IF(J.EQ.3) ICL=95
      IF(J.EQ.4) ICL=99
      K=1
      IF(POOL(1,J).EQ.0.0) GO TO 14
      ISIZE=IFIX(POOL(1,J))+1
      TPOOL=AINT(POOL(1,J))
      IF(TPOOL.GE.POOL(1,J)) ISIZE=IFIX(POOL(1,J))
      GO TO 11
   14 ISIZE=0
   11 PURCST=ISIZE*UC
      DPRCST=ISIZE*UC
      UNTS=ISIZE
      YPC = PURCST
```

```
      THCST=0.0
      DHCST=0.0
      DO 100 I=1,N
      TIME = TIME+TI
C
C  DETERMINE CURRENT SIZE OF POOL
C
      JSIZE=IFIX(POOL(I,J))+1
      IF(AINT(POOL(I,J)).GE.POOL(I,J)) JSIZE=IFIX(POOL(I,J))
      IF(POOL(I,J).NE.0.0) GO TO 12
      GO TO 22
   12 IF(JSIZE.LE.ISIZE) GO TO 22
C
      UNTS=UNTS+JSIZE-ISIZE
C  DETERMINE PURCHASE COST OF INCREASE OF POOL SIZE
C
      PPCST=(JSIZE-ISIZE)*UC
      PURCST=PURCST+PPCST
      YPC=YPC+PPCST
      DPRCST=DPRCST+(PPCST)/((1+RA)**I)
      ISIZE=MAX0(ISIZE,JSIZE)
C
C  TEST FOR COMPLETION OF FISCAL YEAR
C
   22 IF(TIME.GE.52) GO TO 30
      GO TO 24
C
C  COMPUTE PAST YEARS COST
C
   30 TYPC(K)=YPC
      TIME=TIME-52
      FTI=TI-TIME
      PHCST=PURCST*((CHR*FTI)/52)
      TYHC(K)=YHC+PHCST
      UNITS(K)=UNTS
      K=K+1
      YHC=0.0
      YPC=0.0
      PHCST=PURCST*((CHR*(TI-FTI))/52)
      UNTS=0.0
      UC=UC*1.05
      GO TO 25
C
C  DETERMINE CURRENT TIME INCREMENT HOLDING COSTS
C
   24 IF(ISIZE.EQ.0.0) GO TO 100
   23 PHCST=PURCST*((CHR*TI)/52)
   25 YHC=YHC+PHCST
```

```
      THCST=THCST+PHCST
      DHCST=DHCST+(PHCST)/((1+RA)**I)
  100 CONTINUE
      TYPC(K)=YPC
      TYHC(K)=YHC
      UNITS(K)=UNTS
C
C   DISCOUNT ALL COSTS TO 1972 DOLLARS
C
      DPRCST=DPRCST/((1+A)**(STA/52))
      DHCST=DHCST/((1+A)**(STA/52))
      DHCST=DHCST/((1+A)**STIM)
      DPRCST=DPRCST/((1+A)**STIM)
      AURCST(J)=PURCST
      APRCST(J)=DPRCST
      AHCST(J)=THCST
      ADHCST(J)=DHCST
      M=K-1
      WRITE(6,2003) ICL
 2003 FORMAT('0','   CONFIDENCE LEVEL ='I4)
      IYEAR=1973+IFIX(STIM)
      WRITE(6,2001)
 2001 FORMAT('0',T10,'YEAR',T30,'UNITS',T50,'PURCHASE',T70,'HOLDING')
      WRITE(6,2004)
 2004 FORMAT(' ',T30,'PURCHASED',T50,'COSTS',T70,'COSTS')
      DO 999 L=1,M
      WRITE(6,2002) IYEAR,UNITS(L),TYPC(L),TYHC(L)
 2002 FORMAT('0',T10,I4,T30,F4.0,T50,F8.2,T70,F8.2)
      IYEAR=IYEAR+1
  999 CONTINUE
C
C   COST OUT REMAINING LIFE CYCLE
C
      TIME=52-TIME
      NP=IFIX(TIME)+N
      PHCST=PURCST*((CHR*TIME)/52)
      AHCST(K)=AHCST(K)+PHCST
      THCST=THCST+PHCST
      DHCST=DHCST+((PHCST)/((1+RA)**NP))/((1+A)**2)
      TYHC(K)=TYHC(K)+PHCST
      WRITE(6,2002) IYEAR,UNITS(K),TYPC(K),TYHC(K)
      NYR=1994-IYEAR
      DO 998 M=1,NYR
      IYEAR=IYEAR+1
      YHCST=PURCST*CHR
      TYHC(M)=YHCST
      UNITS(M)=0.0
      TYPC(M)=0.0
```

```
      AHCST(J)=AHCST(J)+YHCST
      ADHCST(J)=ADHCST(J)+YHCST/((1+A)**(IYEAR-1973))
      WRITE(6,2002) IYEAR,UNITS(M),TYPC(M),TYHC(M)
  998 CONTINUE
  900 CONTINUE
      WRITE(6,1000)
 1000 FORMAT('1',T2,'CONFIDENCE',T14,'DISCOUNT',T24,'PURCHASE COST',T39,
     C'PURCHASE COST',T54,'HOLDING',T66,'HOLDING COSTS',T81,'HOLDING COS
     XTS',T97,'TOTAL COSTS')
      WRITE(6,1001)
 1001 FORMAT(' ',T2,'LEVEL',T14,'RATE',T24,'UNDISCOUNTED',T39,'DISCOUNTE
     CD',T54,'COST RATE',T66,'UNDISCOUNTED',T81,'DISCOUNTED',T97,'DISCOU
     XNTED')
      DO 990 J=1,4
      IF(J.EQ.1) ICL=75
      IF(J.EQ.2) ICL=85
      IF(J.EQ.3) ICL=95
      IF(J.EQ.4) ICL=99
      TOTAL=APRCST(J)+ADHCST(J)
      WRITE(6,2000) ICL,A,AURCST(J),APRCST(J),CHR,AHCST(J),ADHCST(J),TOT
     CAL
 2000 FORMAT('0',T6,I2,T15,F4.3,T24,F10.2,T39,F10.2,T55,F4.2,T66,F10.2,T
     C81,F10.2,T97,F10.2)
  990 CONTINUE
      RETURN
      END
C
C     NOW ERASE DISK
C
C
C     TWO CARDS FOLLOWING //GO.SYSIN DD * ARE GRAPH LABEL CARDS
C
//GO.FT04F001 DD DSN=&TEMP,DISP=(OLD,DELETE),UNIT=SYSDA
//GO.SYSIN DD *
        CUSHING    1
RUN-122
```

```
*************************************************************************
*************************************************************************
*************************************************************************

THE FOLLOWING SECTIONS ARE INSERTED AS DESIRED AND ARE NOT PART OF THE
BASE CASE PER SE. EACH MAJOR SECTION IS LABELED AS TO WHICH OPTION IT
ANALYZES.  MAJOR SECTIONS ARE DENOTED BY THE DOUBLE ASTERISK BAR.

*************************************************************************
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*************************************************************************



*************************************************************************
*************************************************************************

PURCHASE PLAN OR LOAD OPTION.  THIS SECTION LOADS THE ROTABLE POOL WITH
ENGINES ACCORDING TO ANY PREDETERMINED LOAD POLICY.

*************************************************************************
*************************************************************************



*
*
*      THE FOLLOWING VALUES MUST BE SPECIFIED PRIOR TO RUNNING THIS OPT.
*
*      XH$LOAD"J"==NO. OF ENGINES TO BE LOADED ON LOAD J
*      XH$TIME"K"==TIME DELAY PRIOR TO LOAD K
*
*
 HOLD   MARK
        SPLIT       XH$LOAD1,STOC1
        ADVANCE     XH$TIME2
        SPLIT       XH$LOAD2,STOC1
        ADVANCE     XH$TIME3
        SPLIT       XH$LOAD3,STOC1
        ADVANCE     XH$TIME4
```

```
        SPLIT        XH$LOAD4,STOC1
        ADVANCE      XH$TIME5
        SPLIT        XH$LOAD5,STOC1
        ADVANCE      XH$TIME6
        SPLIT        XH$LOAD6,STOC1
        ADVANCE      XH$TIME7
        SPLIT        XH$LOAD7,STOC1
        ADVANCE      XH$TIME8
        SPLIT        XH$LOAD8,STOC1
        ADVANCE      XH$TIME9
        SPLIT        XH$LOAD9,STOC1
        ADVANCE      XH$TIME0
        SPLIT        XH$LOAD0,STOC1
        TERMINATE    0
*
 STOC1  MARK
        TRANSFER     ,STOCK
*
*
*
*****************************************************************
*
*       THIS LOOP COUNTS THE NO. OF ENGINE HOURS LOST TO THE FLEET
*       DUE TO A STOCKOUT IN THE ROTABLE POOL.
*
*****************************************************************
*
  INFO  MARK
        ASSIGN       7,V$RUNT                  LOOP FOR TOTAL RUNNING TIME
        SAVEVALUE    FIVE+,K1,H                CURRENT RUN NUMBER
 XXX1   MARK
        ADVANCE      1                         CHECK ENG-HRS SHORT EVERY INCRE.
        TEST L       S$NAV,N$COUNT,OUT
        SAVEVALUE    FOUR+,K1,H
        SAVEVALUE    ADD+,V$ENGHR,H            SUM OF OUTAGES FOR THIS RUN
  OUT   LOOP         7,XXX1
*
        TEST NE      XH$FOUR,K0,FINAL
        SAVEVALUE    FOUR,K0,H                 ZERO OUT COUNTER
*
        SAVEVALUE    THREE+,K1,H
        SAVEVALUE    XH$THREE,XH$ADD,H         PLACE RUN SUM IN XH#
```

```
*        SAVEVALUE  ADD,K0,H               RESET TO ZERO
*        SAVEVALUE  SIX+,K1,H              NO. OF RUNS WITH SHORTAGES
*        TEST E     XH$FIVE,XH$NRUNS,FINAL
*
*      ON THE LAST TIME THROUGH TABULATE THE SAVEVALUES
*      CONTAINING ENGINE-HOURS LOST.
         ASSIGN     8,XH$SIX
         ASSIGN     1,K50
   XXX2  MARK
         ASSIGN     1+,1
         ASSIGN     3,XH*1
         TABULATE   V$PLUS
         LOOP       8,XXX2
         TRANSFER   ,FINAL
*
*
*
*
*
```

```
*****************************************************************
*****************************************************************

SPLIT POOL OPTION.  THIS PROGRAM TESTS THE EFFECT OF SPLITTING THE
ROATABLE POOL INTO TWO SECTIONS OF EQUAL SIZE, EACH DRAWN UPON BY HALF
THE FLEET.  NO TRANSPORTATION BETWEEN POOLS IS ALLOWED.

*****************************************************************
*****************************************************************




*
*
*      CREATE ENGINES FOR THIRTY MONTHS
*
*      GENERATE SHIPS ACCORDING TO SCHEDULE
*
       GENERATE    FN$SHIPS,,,30
       SAVEVALUE   INT+,K1,H
*
       SPLIT       1,HERE
*
       SPLIT       1,NEXT,1                  SEND  2 S TC NEXT
*                                            ONE'S FALL THROUGH TO NEXT
  NEXT MARK
*
 CCUNT MARK
*
 FLEET ENTER       *1
*
       SAVEVALUE   OPER,FN22,H
*
       TRANSFER    .XH$RAND.RNAV.RFAIL       RANDOM FAILURES SPLIT HERE
  RNAV ADVANCE     XH$OPER
       LEAVE       *1
  JOIN MARK                                  RANDOMLY FAILED ENGINES REJOIN
       LOGIC S     *1
        ADVANCE    XH$TRANS,1                ARBITRARY TRANSPORT DELAY
       QUEUE       3                         FORM FOR REWORK AT FACILITY
```

```
       ENTER      3                      ENTER REWCRK FACILITY
       DEPART     3
       MARK                              DEBUG
       ADVANCE    FN$LEARN,1             WAIT FOR TIME F(NO OF ENG)- 1
 LEARN LEAVE      3                      LEARNING CURVE KEYS OFF  NO.
*
 STOCK QUEUE      *1
*
*     CHECK TO SEE THAT EACH SHIP HAS FOUR ENGINES, IF NOT ISSUE ONE
*
      TEST E      P1,K1,TWO
       GATE LS    1
       TRANSFER   ,XXX5
   TWO GATE LS    2
       TRANSFER   ,XXX5
*
  XXX5 DEPART     *1                     ISSUE ENGINE FROM POOL 1 OR 2
       LOGIC R    *1
       TEST NE    XH$TALLY,K1,RDLAY      IS THE FAILURE RANDOM?
       TRANSFER   ,FLEET
*
*     RFAIL PACKAGE FOR RANDOM FAILURES
*
 RFAIL MARK
       ADVANCE    V$MEAN,V$MEAN
       SAVEVALUE  TALLY,K1,H             FLAG THE RANDOM FAILURES
       TRANSFER   ,JOIN
*
  HERE MARK
       SPLIT      1,NEXT,1               COPIES WITH 2 TO NEXT
       TRANSFER   ,NEXT                  TRANSFER ALL PARENTS TO NEXT--1
*
 RDLAY MARK
       SAVEVALUE  TALLY,K0,H
       ADVANCE    XH$TRANS,1             ARBITRARY TRANSPORTATION DELAY
       TRANSFER   ,FLEET
*
*     THIS LOADS THE POOL WITH APPROPRIATE NO. ENGINES
*
       GENERATE   ,,,50
       SPLIT      1,STOCK,1              SEND 50 LABELED 2 TO STOCK
       SPLIT      1,STOCK                SEND 50 LABELED 1 TO STOCK
       TERMINATE  0
```

```
****************************************************************
****************************************************************

MANAGEMENT OPTION.  THIS PROGRAM ALLOWS THE DECISION MAKER TO TEST
THE EFFECT OF EXTENDING TBO DEPENDING UPON FACILITY LOAD.  ENGINES MAY
ALOS BE EXTENDED IF THEY ARE IN A DEPLOYED STATUS.

****************************************************************
****************************************************************


 RNAV  MARK
       ADVANCE     V$SMART                ENGINES RUN FOR 90% OF LIFE
       SAVEVALUE   SMART,M1,H             PUT 90% TIME INTO SMART
       ASSIGN      12,M1                  PUT 90% INTO P12
*
*     IF THE SHIP IS ON DEPLOYMENT DELAY THE ENGINE, IF NOT CHECK FAC
*
       TRANSFER    .XH$DPLOY,CHECK,DPLOY
*
*     THE SHIP IS ON DEPLOYMENT
*
 DPLOY SAVEVALUE   DPL01,V$DPLOY,H        STORE 10% TIME HERE
       ADVANCE     XH$DPL01               WAIT 10% NOW AT TBO
       ADVANCE     6,2
       TRANSFER    ,JOIN                  NOW TRANSPORT ENG TO REWORK
*
*     CHECK FACILITY TO DETERMINE IF LOAD IS LIGHT
*
 CHECK SAVEVALUE   CHECK,V$DPLOY,H        PUT 10% INTO CHECK
*
       ASSIGN      9,V$CHECK
 EARLY TEST G      V$LOT,XH$LOT,JOIN      IF FAC DOWN THEN SEND ENG IN NOW
       ADVANCE     1
       LOOP        9,EARLY
       TRANSFER    ,JOIN                  SEND REMAINING ENG. TO REWOK
*
 SMART FVARIABLE   XH$OPER*9/10           90% IO TBC
 DPLOY VARIABLE    P12/9                  10% OF TBO
```

```
************************************************************************
************************************************************************

PF PROGRAM OPTION.  THIS SECTION INCLUDES THOSE ENGINES ADDED FROM THE
PATROL FRIGATE PROGRAM.

************************************************************************
************************************************************************

  USPF MARK
       ADVANCE    XH$PFLAG                PROGRAM DELAY OVER DD963
       ASSIGN     10,K50                  FIFTY SHIPS
  XXX3 SPLIT      2,COUNT                 2 ENGINES PER SHIP
       ADVANCE    4                       LAUNCH/DELIVER ONCE A MONTH
       LOOP       10,XXX3
       TERMINATE  0
*
*
*
*

************************************************************************
************************************************************************

                          END OF PROGRAMS

************************************************************************
************************************************************************
```

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13. ABSTRACT

LM-2500 gas turbine engine rotable pool requirements were studied using computer simulation. System operating characteristics were observed with various scenarios and management philosophies. Several purchase plans were formulated and tested once system trends were established. From this information, cost-effectiveness relationships were derived.

Best estimates of system variables indicated that cost-effectiveness was optimized for a rework capacity of seven to eight engines and the purchase of fourteen to sixteen engines early in system life as rotable pool spares.

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